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RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

IV - PERFORMANCE OF RAM-JET UNITS DESIGNED FOR COMBUSTION-CHAMBER-INLET MACH NUMBER OF 0.21 AT FREE-STREAM MACH NUMBER OF 1.6 OVER A RANGE OF FLIGHT CONDITIONS

By Leonard Rabb and Warren J. North

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Cleveland, Ohio

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RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

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SUMMARY

An investigation of 16-inch-diameter ram-jet units under free-flight conditions was conducted to determine performance at high subsonic, transonic, and supersonic velocities. Full-scale units were released from an airplane at high altitudes and accelerated by the engine thrust and the force of gravity. Data for evaluating the performance were obtained from radio-telemetering and radar-tracking equipment.

Performance data of four C-type ram-jet units are presented. The effects of free-stream Mach number and gas total-temperature ratio on diffuser pressure recovery, external drag coefficient, and thrust coefficient are correlated. The range of free-stream Mach number was from 0.43 to 1.83 and the gas total-temperature ratio varied from 1.0 to 4.8. Combustion data with stability limits are also presented.

A lean combustion limit was observed at a fuel-air ratio of 0.032. At a higher fuel-air ratio of 0.059, combustion was not observed below 2154 pounds per square foot. The transonic minimum external drag coefficient increased from 0.14 at a free-stream Mach number of 0.87 to a maximum of 0.31 at a Mach number of 1.20. A maximum thrust coefficient of 0.73 was observed at a free-stream Mach number of 1.64, gas total-temperature ratio of 4.2, and net acceleration (excluding gravity) of 4.3 g's.

INTRODUCTION

As part of a comprehensive study of the performance of ram-jet engines, the NACA Lewis laboratory is conducting free-flight investigations of 16-inch-diameter ram-jet units. The purpose of the investigations is to provide performance and operational data at subsonic, transonic, and supersonic velocities of full-scale ram-jet engines operating under actual flight conditions over a range of combustion-chamber-inlet velocities and fuel-air ratios. 1394

The investigations are being conducted off the Virginia coast near the NACA Langley laboratory. The ram-jet units are released from an airplane at high altitudes and accelerated to supersonic velocities by the engine thrust and the force of gravity. In order to obtain data over a range of combustion-chamber-inlet velocities, four ram-jet designs (designated 16-A, 16-B, 16-C, and 16-D) of varying inlet and outlet areas are being investigated. The results obtained from designs 16-A, 16-B, and 16-D are presented in references 1 to 3, respectively. Several ram-jet units of each design are being investigated in order to obtain data at different fuel-air ratios. The fuel requirements of the engine are met by presetting a fuel regulator that is actuated by free-stream total pressure. Continuous records of data are obtained from radio-telemetering and radar-tracking equipment throughout the flight.

Four ram-jet units of the C type, designed for a combustion-chamber-inlet Mach number of 0.21 at a free-stream Mach number of 1.6, are discussed herein. Time histories of the performance are presented for altitudes from 35,000 feet to sea level and free-stream Mach numbers from 0.43 to 1.83. The effects of free-stream Mach number and gas total-temperature ratios on diffuser pressure recovery, drag coefficient, and thrust coefficient are correlated. Combustion data with stability limits are also presented.

APPARATUS

The four C-type units discussed herein are designated 16-C-1, 16-C-4, 16-C-5, and 16-C-6. (Unit 16-C-2 duplicated data already presented; 16-C-3 data were unavailable because of a failure in both the telemetering and the radar records.) The units are designed for a combustion-chamber-inlet Mach number of 0.21 at a free-stream Mach number of 1.6 and a gas total-temperature ratio of 3.9 with a normal shock at the inlet. The lip of the diffuser is so located as to intercept the oblique shock from the spike in the central body (reference 4) at a free-stream Mach number of 1.8.

A photograph of a typical ram-jet flight installation is shown in figure 1 and a cutaway view of a typical ram-jet unit is shown in figure 2. All pertinent dimensions of the C-type ram-jet unit are given in figure 3. Ram-jet unit C-6 is $8\frac{3}{8}$ inches longer than
1394 the other C-type models. By the addition of the extra length, the fuel capacity is increased from $8\frac{1}{2}$ to 10 gallons.

The fuel system is illustrated in figure 4. The fuel is contained in a flexible rubber bag that is surrounded by helical tubes containing helium at a pressure of 3600 pounds per square inch. The amount of regulated helium pressure available to collapse the fuel cell is proportional to the available free-stream total pressure. The fuel is forced through spring-loaded reducing valves and out spray nozzles into the combustion chamber. Ram-jet unit C-1 had three spring-loaded reducing valves, whereas models C-4, C-5, and C-6 had four spring-loaded reducing valves. These valves open at successively higher regulated pressures, which permits the use of high pressures at comparatively low flow rates. The arrangements of the spray nozzles are shown in figure 5. The fuel used was 80-octane gasoline [AN-F-48b, Amendment-1, grade 80 (unleaded white gasoline)].

Ram-jet unit C-1 used a ducted-airfoil-type flame holder, as shown in figure 6. All other models used a rake-type flame holder (fig. 7). The telemetering section, without the batteries, is shown in figure 8. The tail fins were slotted in an effort to minimize thermal stresses and were riveted to the ram-jet shell, as shown on a typical installation in figure 9.

A more complete description of the apparatus, the instrumentation, the procedure, the general method of calculation, and the equations and notation used in the performance computations is included in reference 2.

RESULTS AND DISCUSSION

Of the four models discussed, one (C-5) had smooth burning for the greater part of its flight, two (C-1 and C-6) exhibited rough burning, and the other (C-4) did not burn at any time because of a failure in the fuel system.

Time histories of the ram-jet units are presented in figures 10 to 13. These figures have been arranged in groups describing: (a) resultant flight conditions, (b) independent variables, (c) diffuser variables, (d) combustion-chamber-inlet variables, and (e) performance variables. The dashed lines indicate approximate values of the data.

Diffuser Total-Pressure Recovery

The correlation between the diffuser total-pressure recovery, the gas total-temperature ratio across the combustion chamber, and the free-stream Mach number is shown in figure 14. Theoretical values of diffuser total-pressure recovery at a free-stream Mach number of 1.8 and gas total-temperature ratios of 2.0 and 3.0 are based on one-dimensional flow. Lines of constant gas total-temperature ratio have been faired according to the collective data points. The dashed line represents the transition from a shock existing within the diffuser to no shock within the diffuser. The position of this line was determined by calculating the values of the gas total-temperature ratio necessary to keep the shock at the inlet (critical heat addition) as a function of free-stream Mach number and fairing this computed curve through the experimental values of heat addition. At a free-stream Mach number of 1.71, at which the value for critical heat addition is 4.0, the pressure recovery for this diffuser was 0.84.

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Drag

The external drag has been defined as the total change in momentum of the air flowing outside the ram-jet unit and therefore includes the additive drag at the diffuser inlet as well as the total external drag on the shell and the fins. Thus, a heat addition sufficient to alter the flow conditions forward of the diffuser inlet would change the external drag coefficient because of the effect on additive and pressure drag.

Drag points from units C-1, C-5, and C-6 at Reynolds numbers between 10^7 and 10^8 were compared (fig. 15) with the turbulent-friction drag coefficient as given in reference 5 for various Mach numbers. In the subsonic Mach number range, the average difference of 0.0005 between calculated external drag coefficient and smooth flat-plate drag may be attributed to pressure drag and additive drag (reference 4). In the transonic range, where the drag coefficient increases abruptly, the drag rise is indicative of the marked effects of additive and pressure drag.

The external drag coefficient is also shown in figure 16 for a range of free-stream Mach numbers from 0.58 to 1.64 and gas total-temperature ratios of 1.0 to 4.8.

A dashed line has been drawn through the data that are believed to represent minimum drag. This minimum drag would result from heat additions below the critical value that would allow the maximum possible air flow through the unit. This critical heat addition would vary from a gas total-temperature ratio of 1.0 at a free-stream Mach number of 0.6 to a gas total-temperature ratio of 3.9 at a free-stream Mach number of 1.6 (fig. 14).

1394 The drag coefficient decreases from 0.185 to 0.14 as the free-stream Mach number increases from 0.58 to 0.87 (fig. 16). A transonic-drag increase occurs between free-stream Mach numbers of 0.87 and 1.20. Reliable data in this region for burning units were unavailable, which prevented an evaluation of additive drag in the transonic range. Ram-jet units C-6 and C-1, however, gave good drag data in the transonic range for zero heat addition.

Thrust Coefficient

The thrust coefficient shown in figure 17 is defined in reference 1 as the net thrust divided by free-stream incompressible dynamic pressure and cross-sectional area. The net thrust is the difference in momentum between free-stream and exit conditions for the air passing through the ram jet where the pressure term has been referred to free-stream static pressure. The maximum obtained thrust coefficient of 0.73 was observed at a free-stream Mach number of 1.64, a gas total-temperature ratio of 4.2, and a net acceleration (excluding gravity) of 4.3 g's. For blow-out conditions, the thrust coefficient remained fairly constant at -0.4.

Combustion

Combustion stability limits were encountered in all three models that burned. These data are presented in table I. Unit C-1 operated at fuel-air ratios from 0.060 to 0.070 and encountered rough burning when approaching the rich limit. Ram-jet unit C-5 ignited at a fuel-air ratio of 0.036, combustion-chamber-inlet velocity of 256 feet per second, combustion-chamber-inlet static pressure of 1236 pounds per square foot absolute, and combustion-chamber-inlet temperature of 520° R. Figure 18(a) shows a sample of the telemeter record at this ignition condition and figure 18(b) is a photographic record of this ignition. A condition of lean instability was approached with unit C-5 (fig. 19) under conditions of combustion-chamber-inlet pressure, temperature, velocity, and fuel-air ratio of 9042 pounds per square foot absolute, 893° R, 338 feet per second, and 0.037, respectively. At these same conditions, maximum combustion efficiency of 98 percent was observed.

Unit C-6 experienced both lean- and moderately rich-ignition conditions. This unit had a lean ignition at combustion-chamber-inlet conditions of static pressure, temperature, velocity, and fuel-air ratio of 1153 pounds per square foot, 520° R, 344 feet per second, and 0.033, respectively. Richer ignition occurred at combustion-chamber- 1394
inlet conditions of pressure, temperature, velocity, and fuel-air ratio of 2154 pounds per square foot, 575° R, 336 feet per second, and 0.059, respectively. Two additional ignition points occurred at fuel-air ratios of approximately 0.048 and 0.046 and combustion-chamber-inlet conditions of pressure, temperature, and velocity of 750 and 800 pounds per square foot, 480° and 520° R, and 286 and 293 feet per second, respectively.

The range of combustion for the 16-C-5 ram-jet unit with a rake-type flame holder (fig. 7) is shown in figure 19. Combustion-chamber-inlet static pressure is plotted against fuel-air ratio with values of combustion-chamber temperature corresponding to given pressures shown as another ordinate. Lines of constant combustion efficiency are faired through the data points and values of combustion efficiency and combustion-chamber-inlet velocity are shown as parameters. Other factors such as fuel distribution and fuel atomization, which affected combustion, could not be evaluated. In order to complete the range of combustion limits, points from the 16-B and 16-D models (references 2 and 3, respectively) with the same type of flame holder are added to the curve.

A lean fuel-air-ratio limit was observed to be 0.032, whereas the rich limit was affected by the combustion-chamber-inlet static pressure. Combustion was not observed below a combustion-chamber-inlet static pressure of 2154 pounds per square foot at a fuel-air ratio of 0.059 and combustion-chamber-inlet velocity of 336 feet per second. For the fuel-air ratios of 0.033 and 0.048, combustion was not observed below a combustion-chamber-inlet pressure of 1153 and 710 pounds per square foot with corresponding velocities of 344 and 286 feet per second.

Figure 20 shows the variation of the fuel-consumption parameter $\frac{\eta_b W_f \times 3600}{F_n - D}$ with free-stream Mach number for various gas total-temperature ratios. Lines of constant heat addition are drawn through the data points and a minimum value of 4.3 ((lb fuel/hr)/lb thrust - drag) was observed near the design Mach number of 1.6 and gas total-temperature ratio of 3.9. The fuel-consumption parameter reaches a minimum value at the free-stream Mach number and total-temperature ratio that position the shock near the lip of the diffuser. At a given free-stream Mach number, heat addition below and above this critical value would increase the fuel-consumption parameter. For less than critical heat addition, the increase would be due to the loss of thrust accompanying the drop in pressure recovery when the shock is swallowed. At higher heat addition, the effect of additive drag is to reduce the thrust minus drag, with the resulting increase in the fuel-consumption parameter.

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SUMMARY OF RESULTS

The following results were observed from the data of four 16-inch-diameter supersonic ram-jet units operating under a range of Mach numbers from 0.43 to 1.83 and gas total-temperature ratios of 1.0 to 4.8:

1. At a constant free-stream Mach number, a decrease in gas total-temperature ratio was accompanied by a decrease in diffuser total-pressure recovery.

2. The minimum drag coefficient decreased from 0.185 to 0.14 as the free-stream Mach number increased from 0.58 to 0.87. A transonic drag rise between free-stream Mach numbers of 0.87 and 1.20 raised the minimum drag coefficient from 0.14 to 0.31. Beyond a Mach number of 1.2, the minimum-drag-coefficient curve gradually decreased to 0.24 at free-stream Mach number of 1.58.

3. The maximum thrust coefficient of 0.73 was observed at a free-stream Mach number of 1.64, a gas total-temperature ratio of 4.2, and a net acceleration (excluding gravity) of 4.3 g's. For no heat addition, the thrust coefficient remained fairly constant at -0.4.

4. A lean fuel-air ratio limit was observed to be 0.032, whereas the rich limit was affected by the combustion-chamber-inlet static pressure. Combustion was not observed below a combustion-chamber-inlet static pressure of 2154 pounds per square foot at a fuel-air ratio of 0.059 and combustion-chamber-inlet velocity of 336 feet per second. For fuel-air ratios of 0.033 and 0.048, combustion was not observed below a combustion-chamber-inlet pressure of 1153 and 710 pounds per square foot with corresponding velocities of 344 and 286 feet per second.

5. The observed minimum value of the fuel-consumption parameter of 4.3 ((lb fuel/hr)/lb thrust - drag) occurred near the design Mach number of 1.6 and heat addition of 3.9.

6. A maximum free-stream Mach number of 1.83 was obtained in unit 16-C-5 with a combustion efficiency of 98 percent, a gas total-temperature ratio of 3.6, and a thrust coefficient of 0.61. 1394

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Cleveland, Ohio.

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TABLE I - COMBUSTION STABILITY LIMITS

Model	Time (sec)	Fuel-air ratio	Combustion-chamber-inlet variables			Condition (a)
			Velocity (ft/sec)	Pressure (lb/sq ft)	Temperature (°R)	
C-1	20.0-41.7	0.060-.070	240-290	1100-3000	490-610	Poor burning with associated vibration of 15-30 cps ranging from small to large amplitude
C-5	27.4	0.036	256	1236	520	Ignition, followed by smooth burning
C-5	44.4	0.037	338	9042	893	Approaching blow-out, preceded by high frequency (67 cps) burning of gradually increasing amplitude
C-6	34.4	0.033	344	1153	560	Ignition, followed by high frequency (51 cps) low-amplitude burning
C-6	23.48	0.046[b]	293	830	517	Ignition, followed by smooth burning
C-6	19.0	0.048[b]	286	710	483	Ignition, followed by fairly smooth burning
C-6	50.0	0.059	336	2154	611	Ignition, followed by low frequency (39 cps) and large amplitude

[a]Rich burning (fuel-air ratio greater than 0.060) has associated low frequency (15-40 cps) and large amplitude. Lean burning has associated high frequency (50-70 cps) and small amplitude.
[b]Approximate values.

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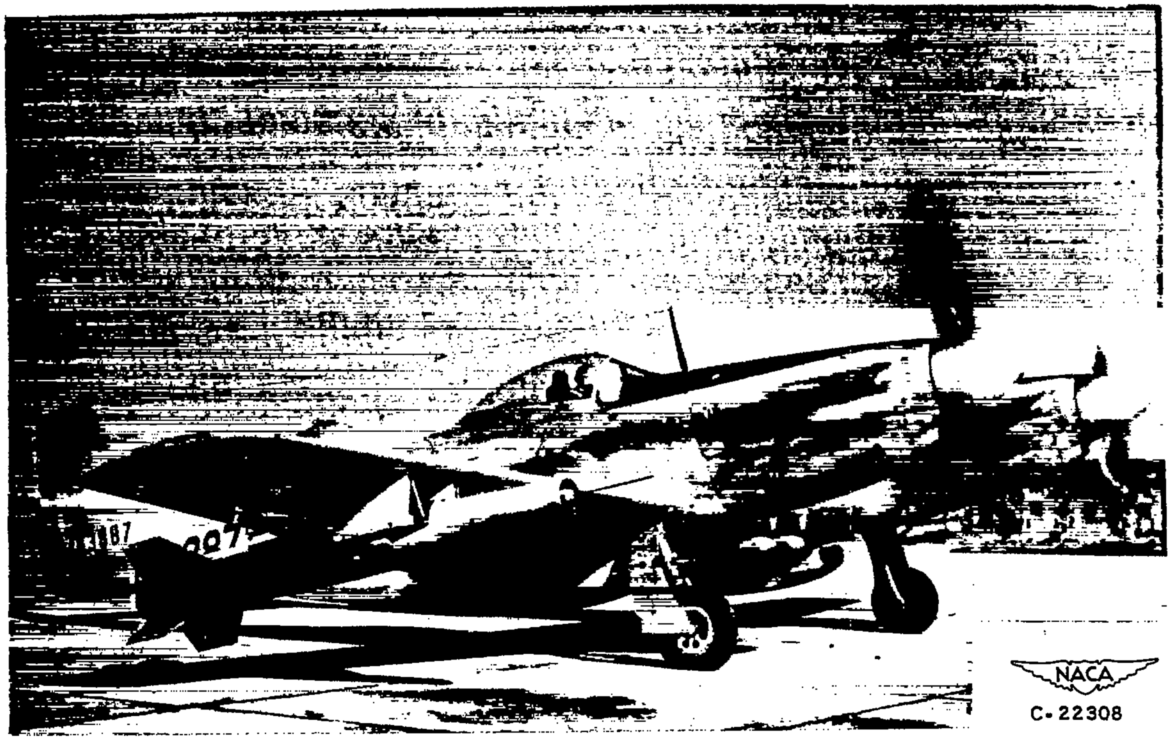


Figure 1. - 16-inch supersonic ram-jet unit mounted beneath airplane wing.

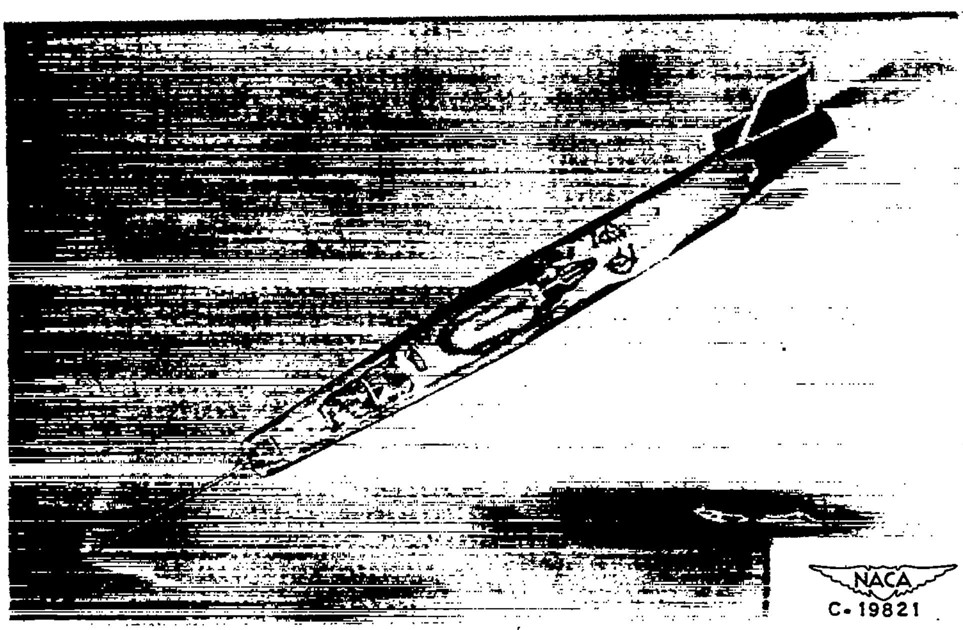
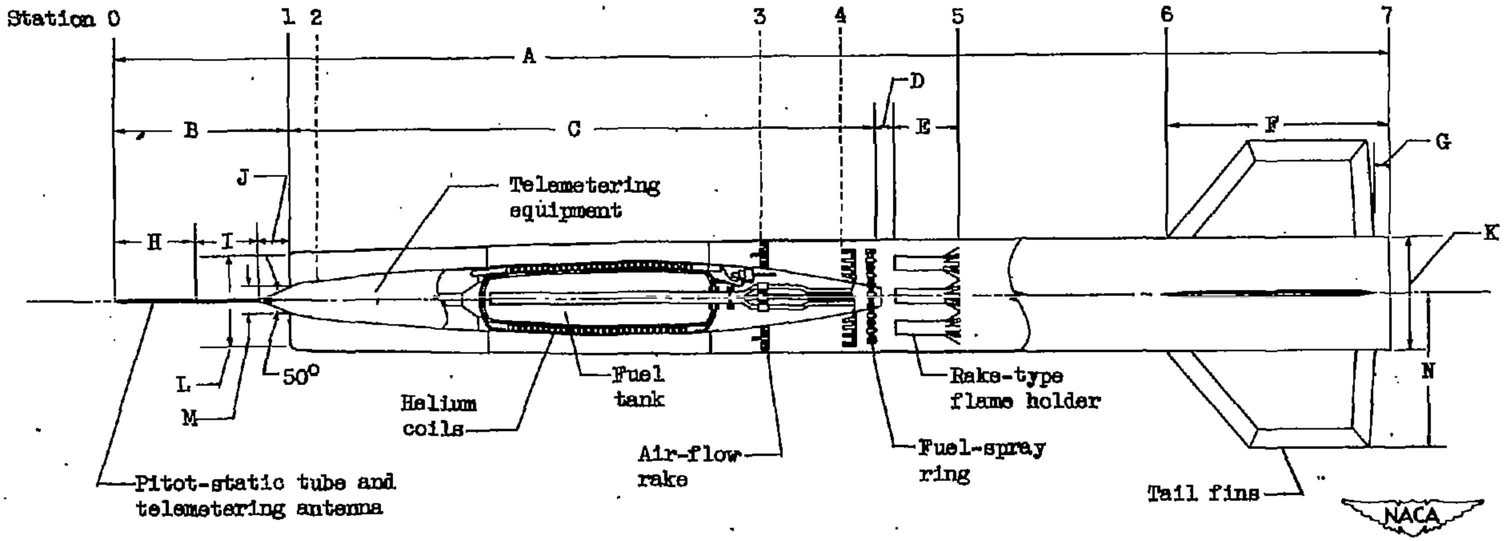


Figure 2. - Cutaway view of 16-inch ram-jet unit during free flight.



Model	A	B	C	D	E	F	G	H	I	J	K	L	M	N
C-1,2,3,4,5	189.71	27.06	86.43	3.00	10.00	34.20	2.00	10.00	12.25	4.82	15.94	10.25	3.51	22.00
C-6	198.09	27.06	94.81	3.00	10.00	34.20	2.00	10.00	12.25	4.82	15.94	10.25	3.51	22.00

Figure 3. - Schematic cross-sectional diagram of supersonic 16-inch-diameter ram-jet unit. Dimensions given for units C-1, C-2, C-3, C-4, C-5, and C-6.

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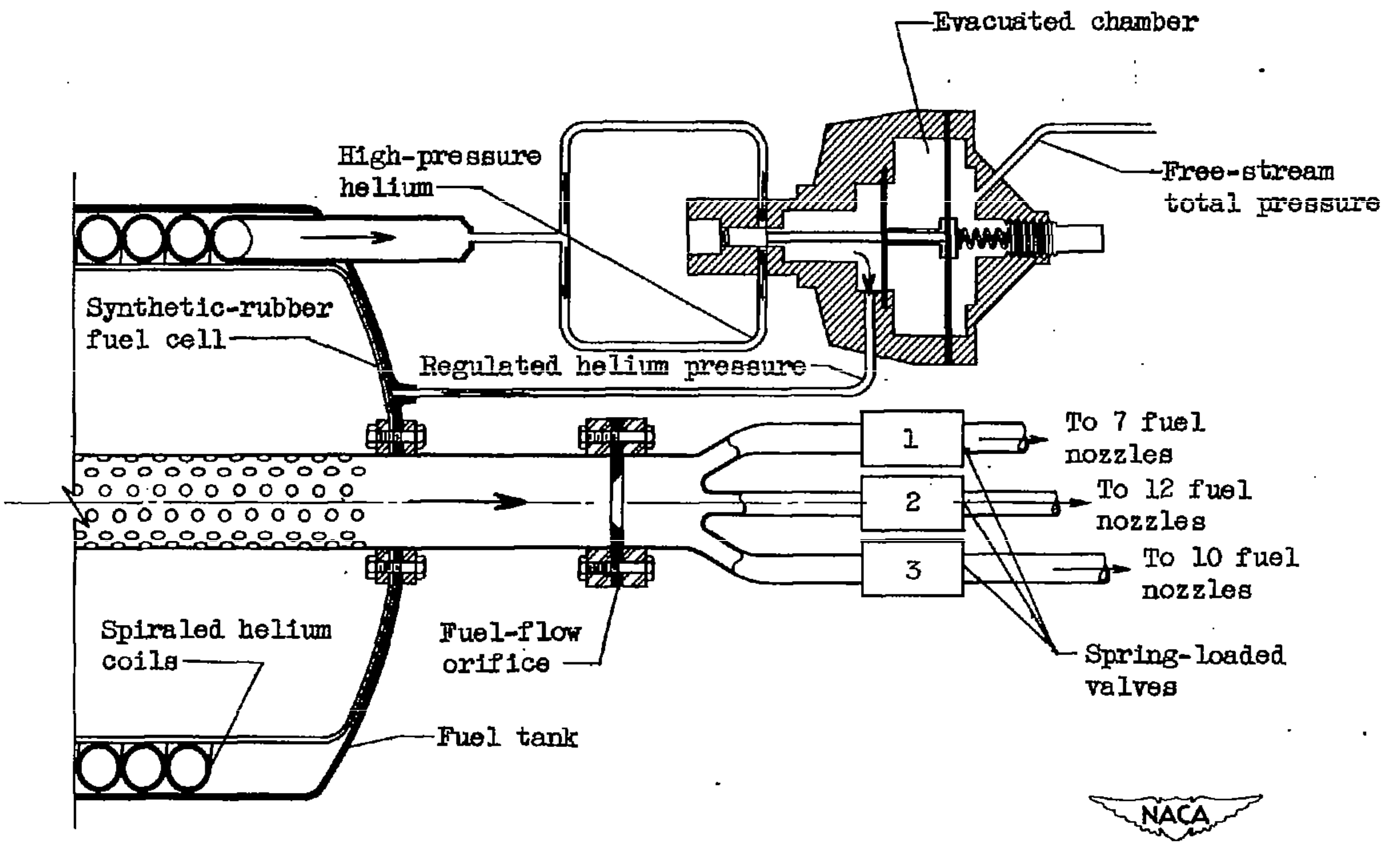

Figure 4. - Schematic diagram of fuel system for supersonic 16-inch ram-jet unit.

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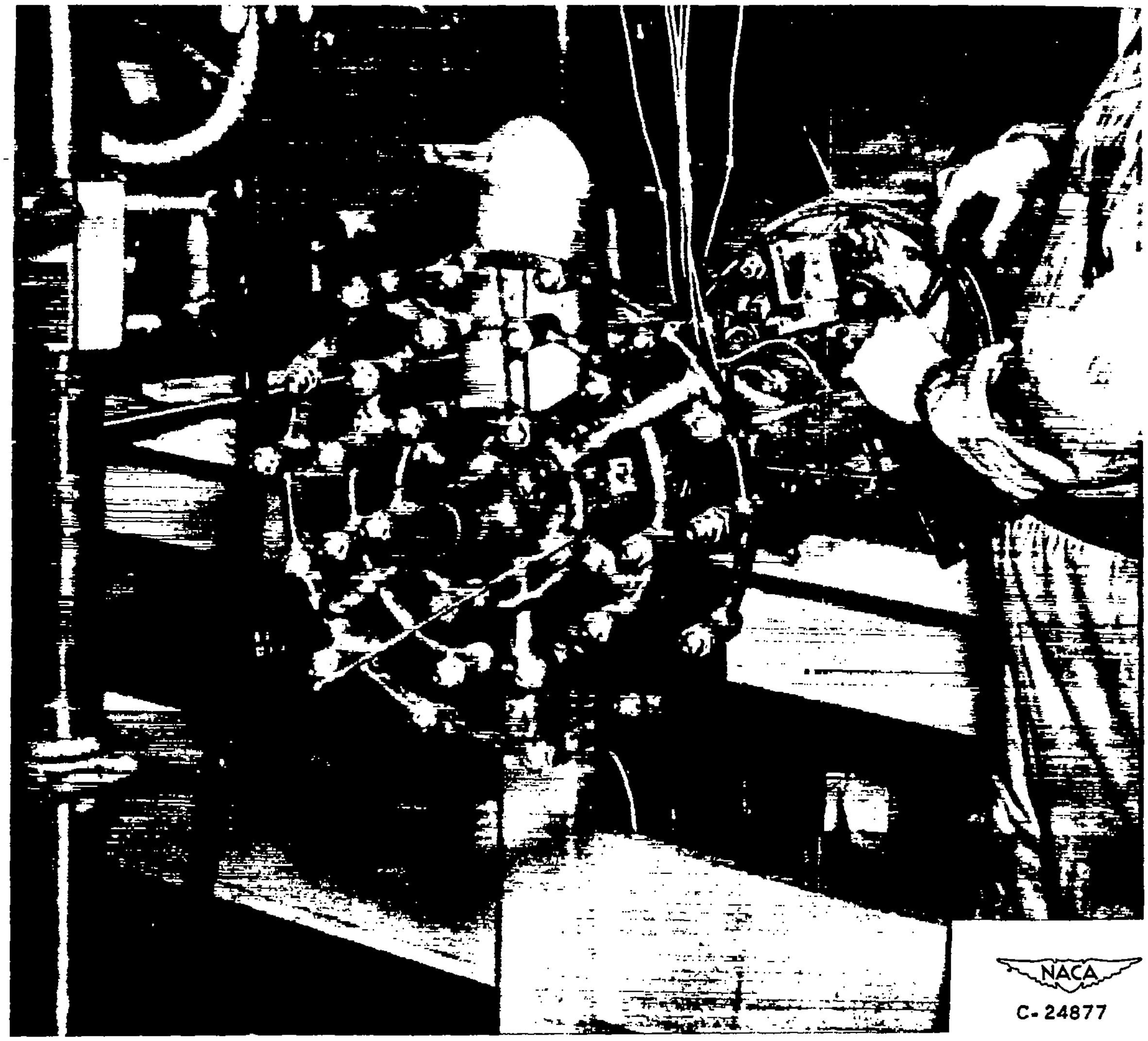

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Figure 5. - Nozzle arrangement on spray bar.

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(a) Three-quarter front view.

(b) Three-quarter rear view.

Figure 6. - Ducted-type flame holder for supersonic ram-jet unit 16-C-1.

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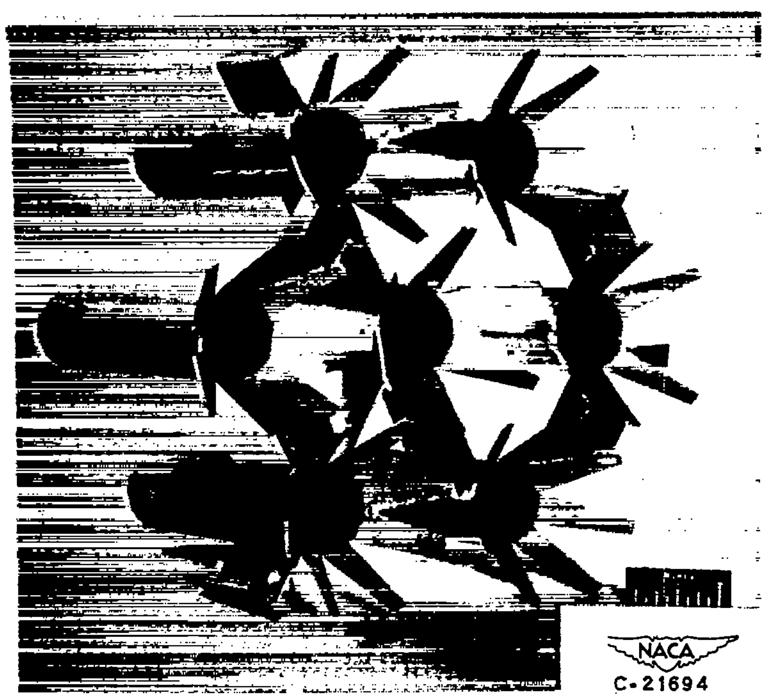
(a) Rear view.



(b) Three-quarter rear view.

Figure 7. - Rake-type flame holder for supersonic ram-jet unit 16-C-4, 16-C-5, and 16-C-6.

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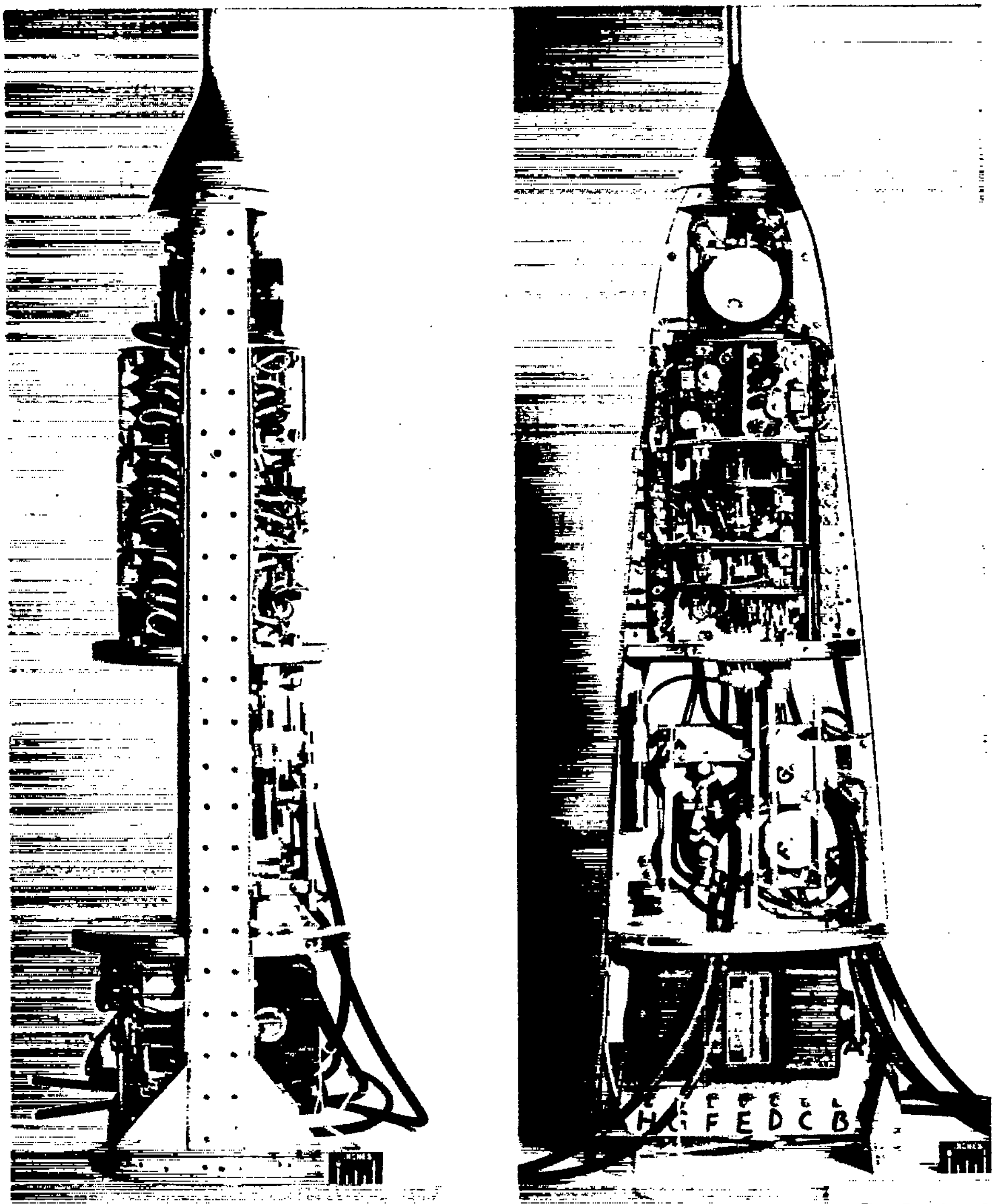

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Figure 8. - Telemetering section used in 16-inch supersonic ram-jet unit.

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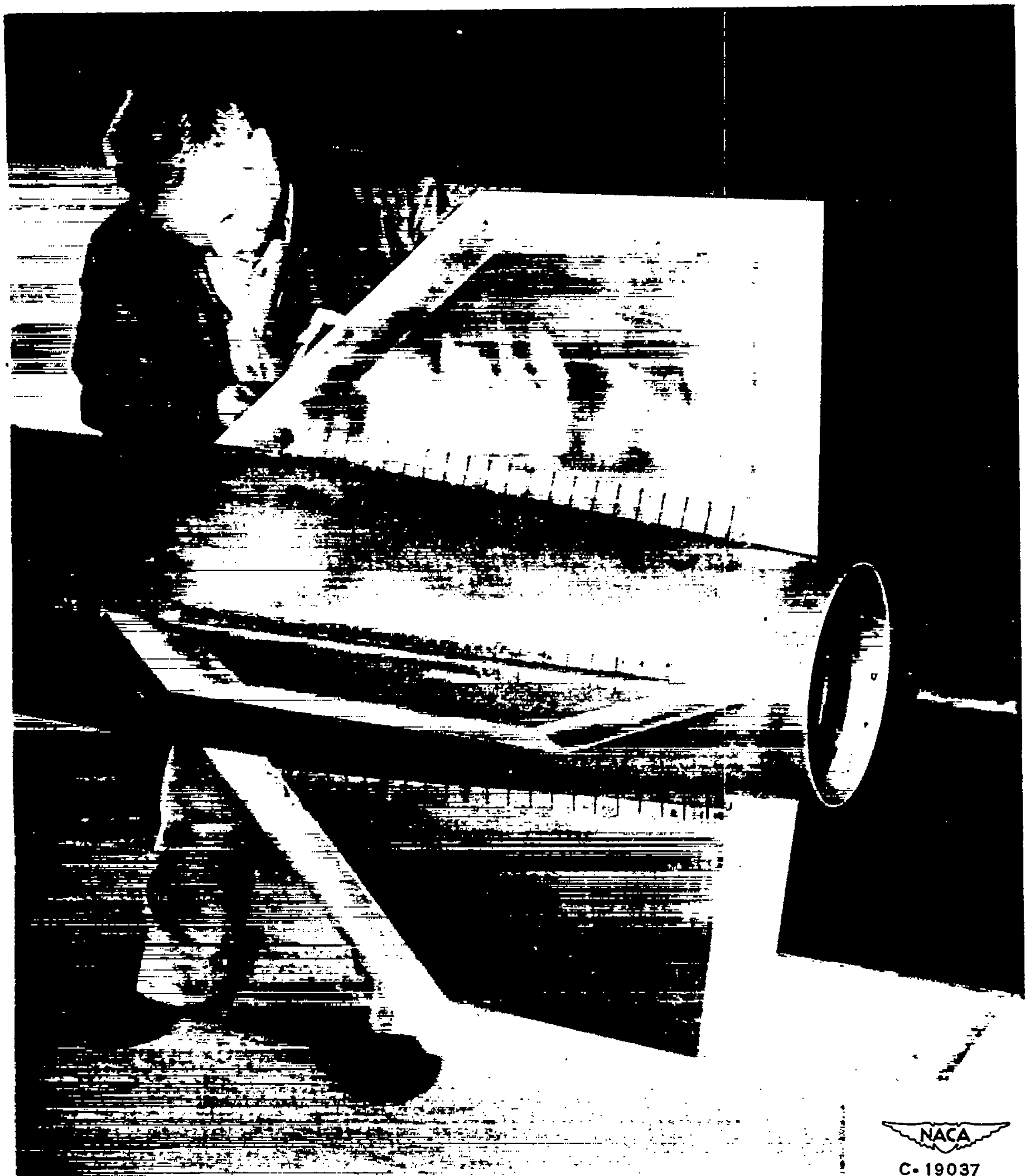

Figure 9. - Typical fin installation on 16-inch supersonic ram-jet unit.

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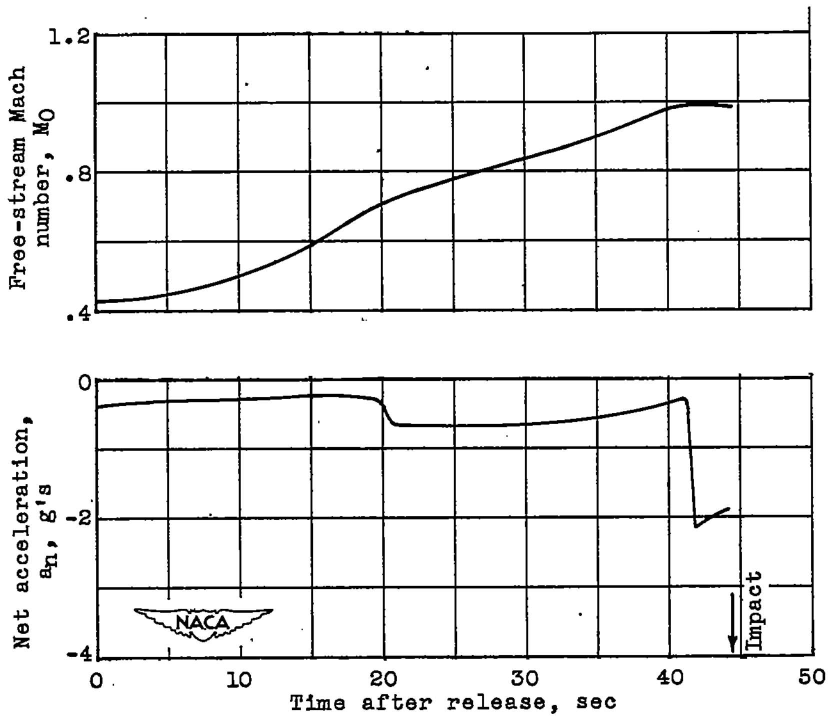

(a) Resultant flight conditions.

Figure 10. - Time history of flight data and performance of ram-jet unit 16-C-1.

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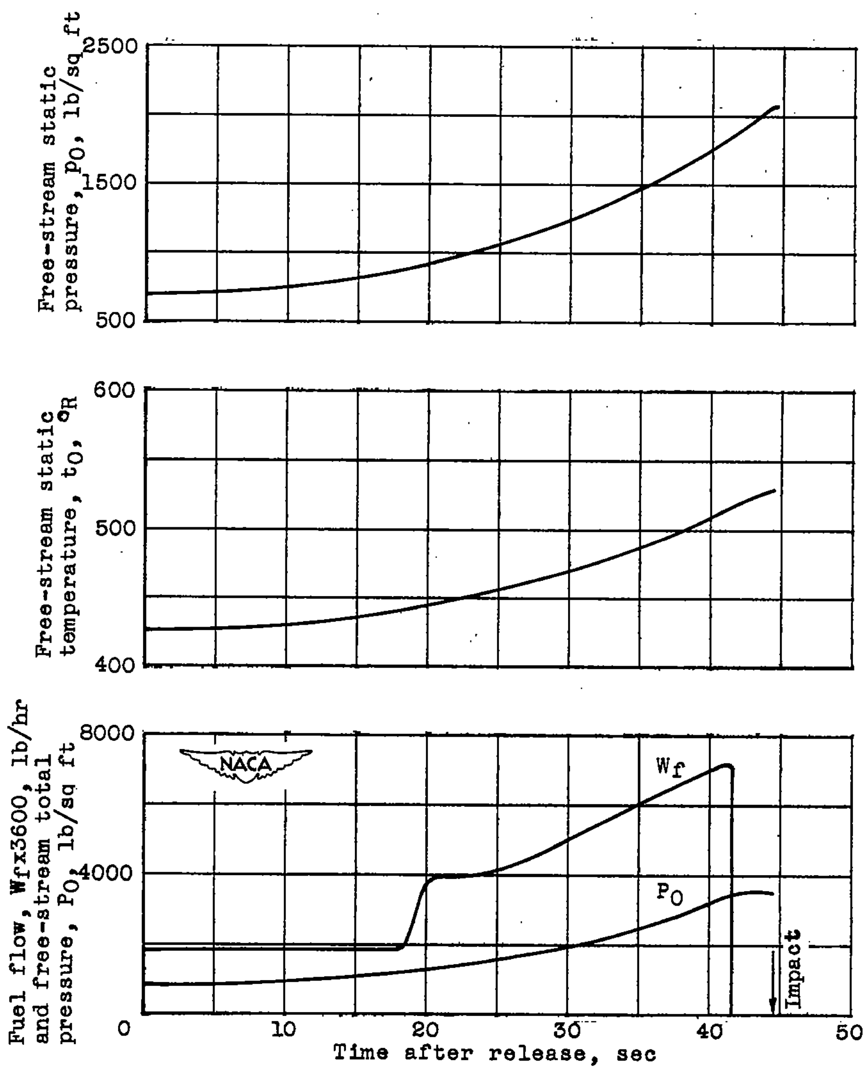

(b) Independent variables.

Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-C-1.

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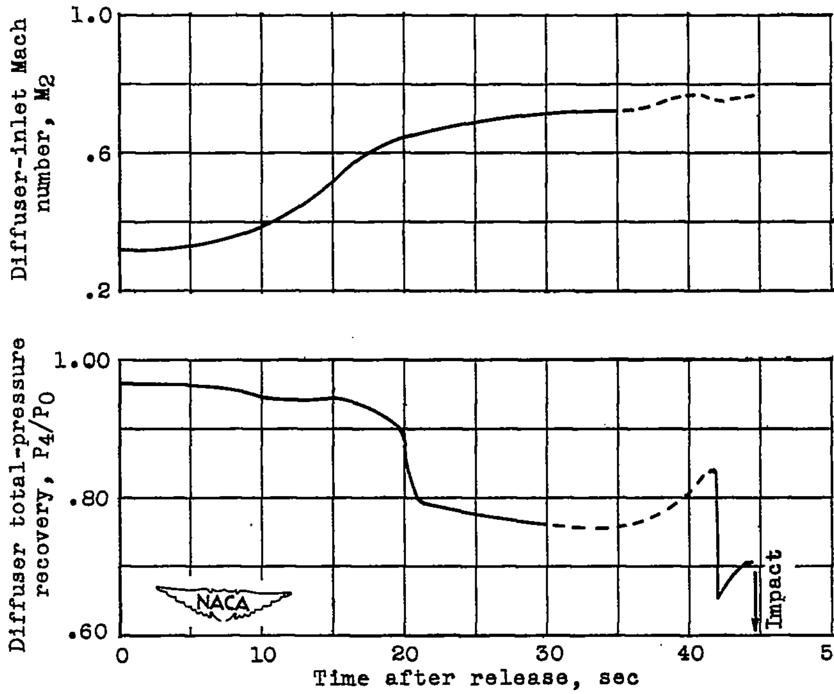
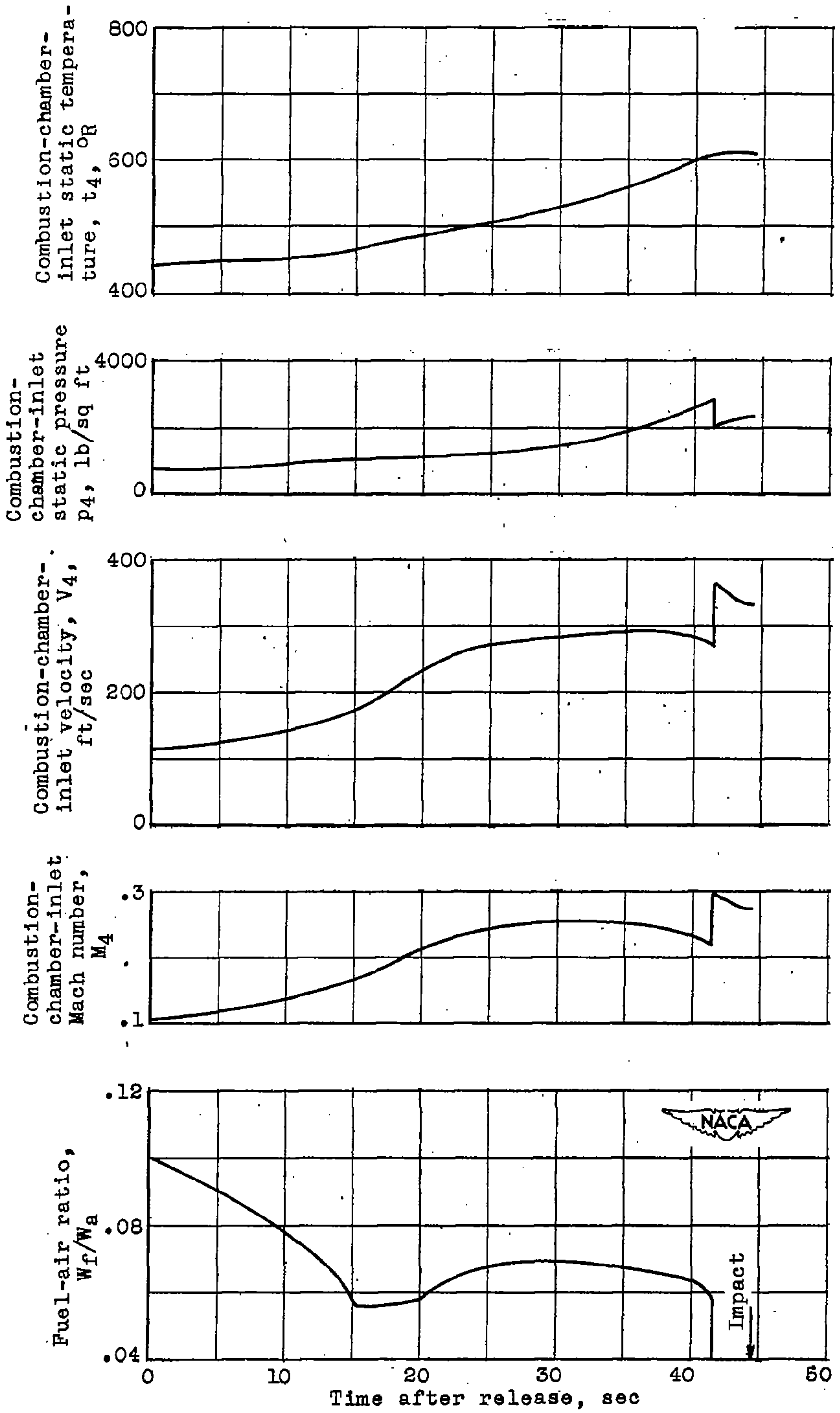


(c) Diffuser variables.

Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-C-1.



(d) Combustion-chamber-inlet variables.

Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-C-1.

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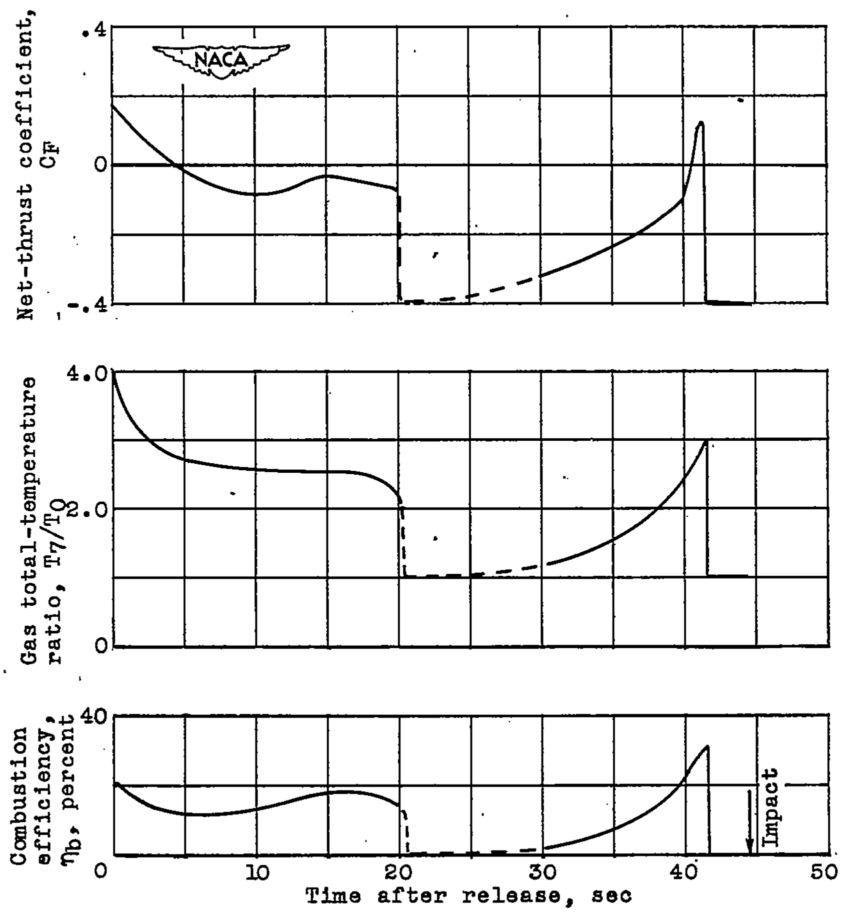

(e) Performance variables.

Figure 10. - Concluded. Time history of flight data and performance of ram-jet unit 16-C-1.

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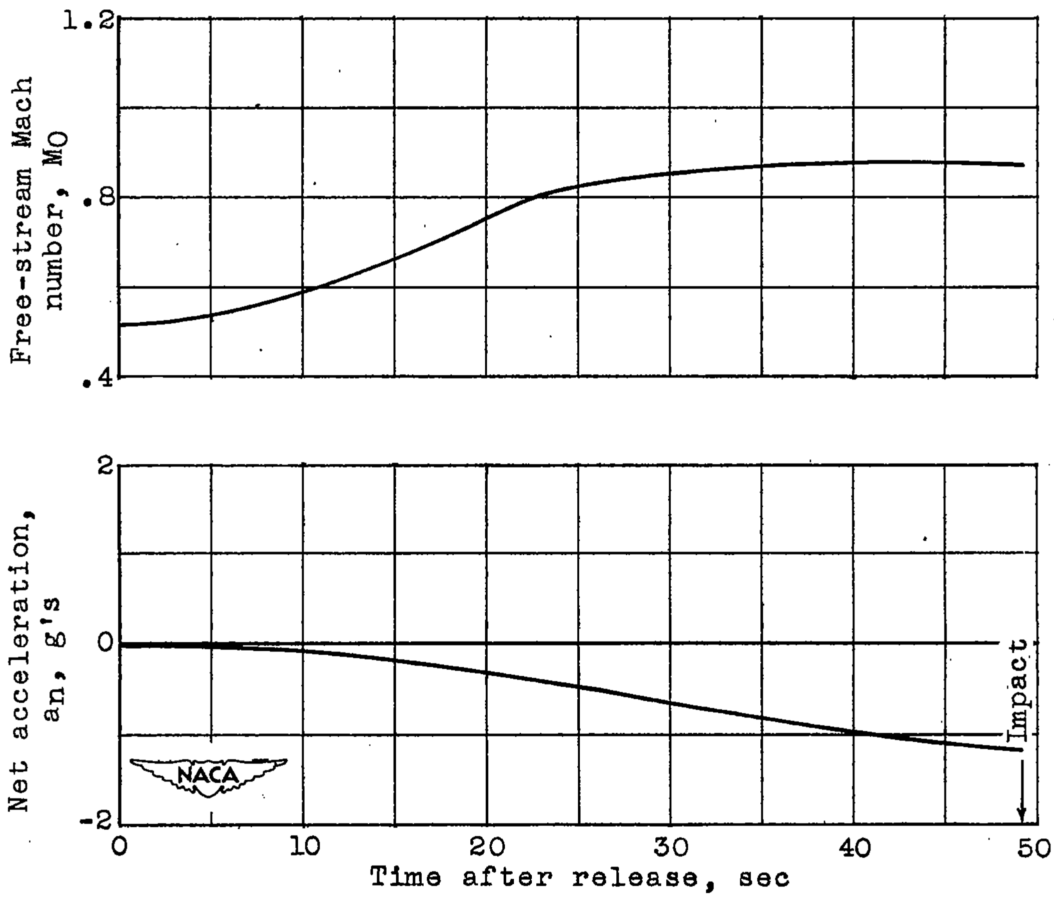

(a) Resultant flight conditions.

Figure 11. - Time history of flight data and performance of ram-jet unit 16-C-4.

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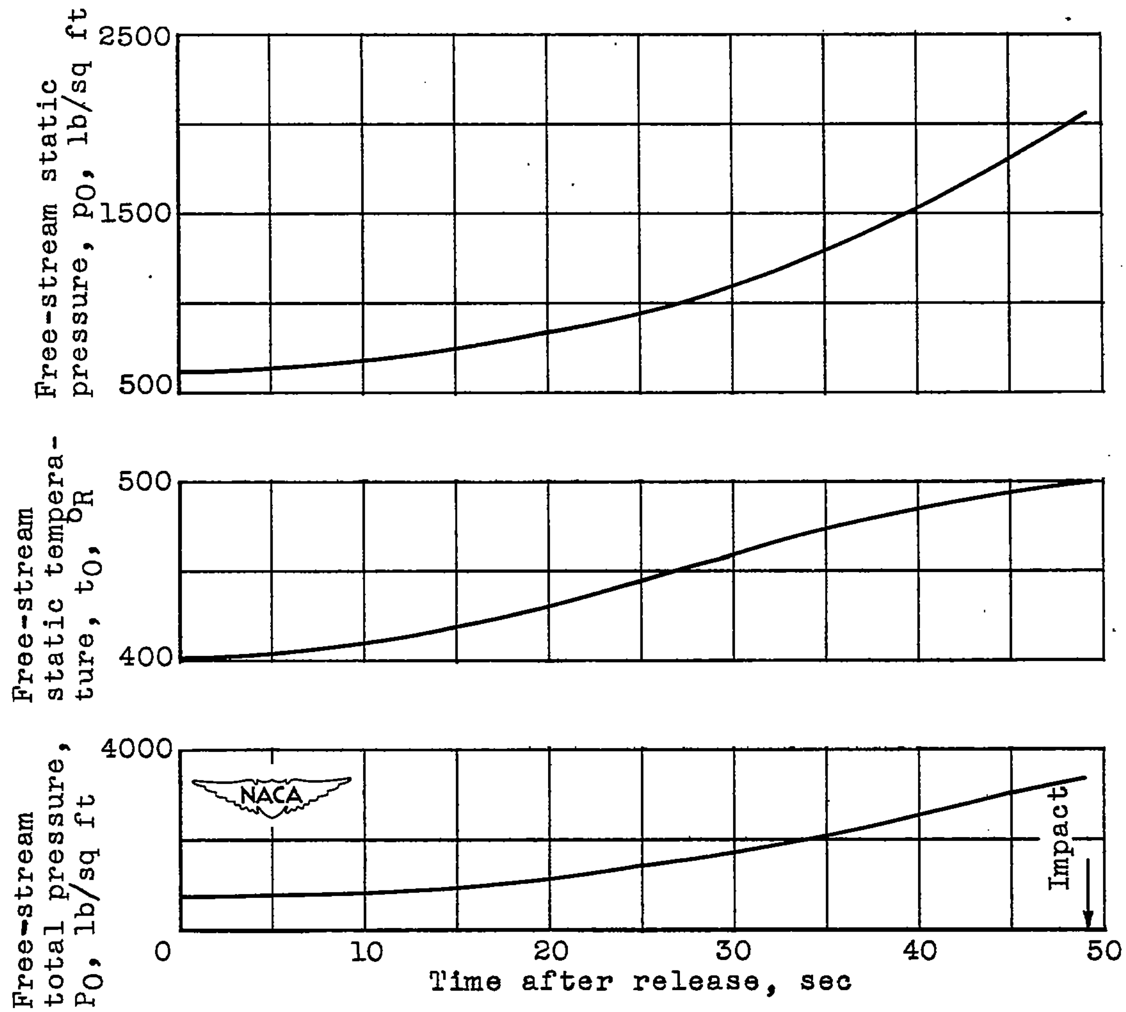

(b) Independent variables.

Figure 11. - Concluded. Time history of flight data and performance of ram-jet unit 16-C-4.

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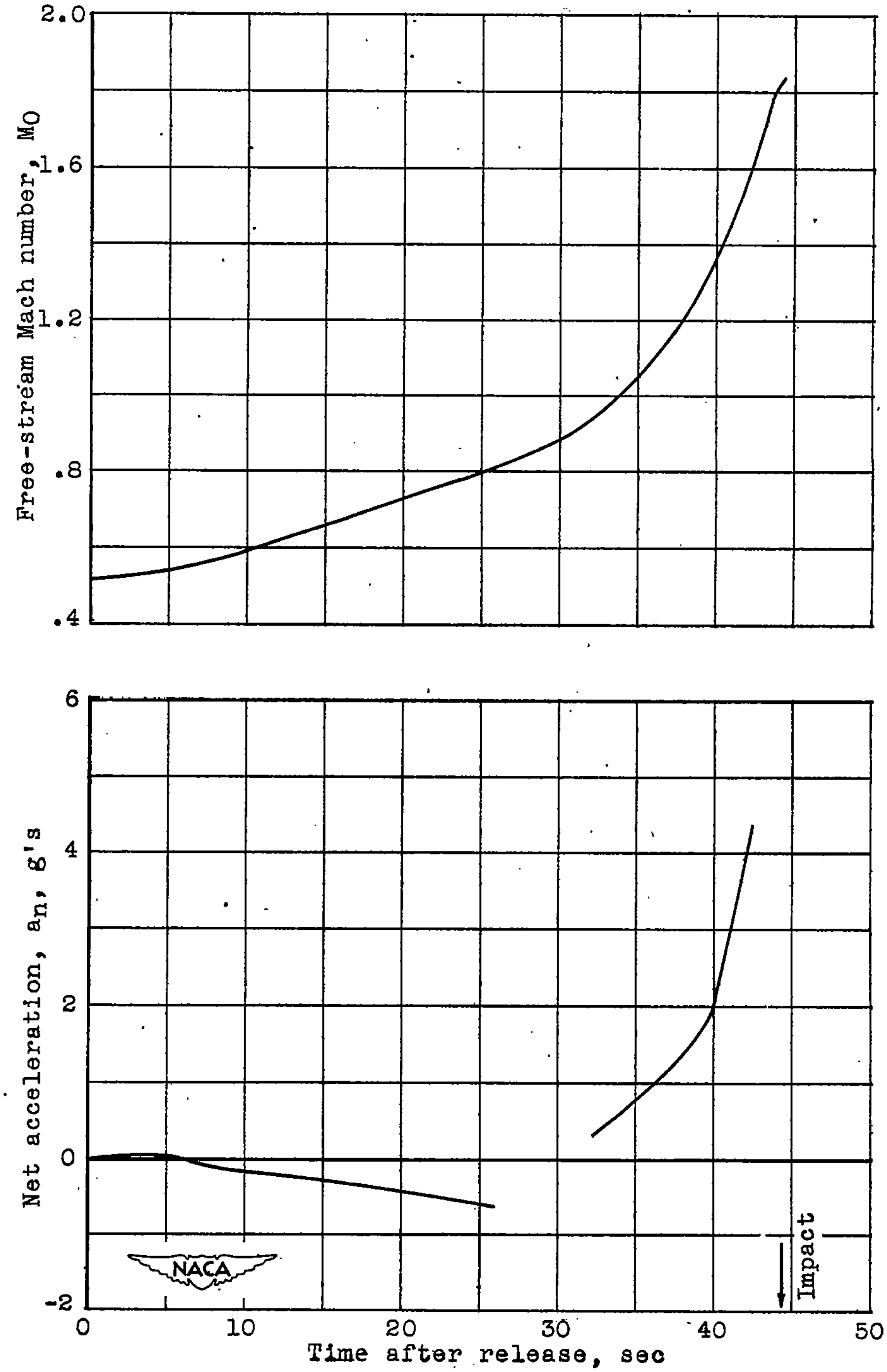

(a) Resultant flight conditions.

Figure 12. - Time history of flight data and performance of ram-jet unit 16-C-5.

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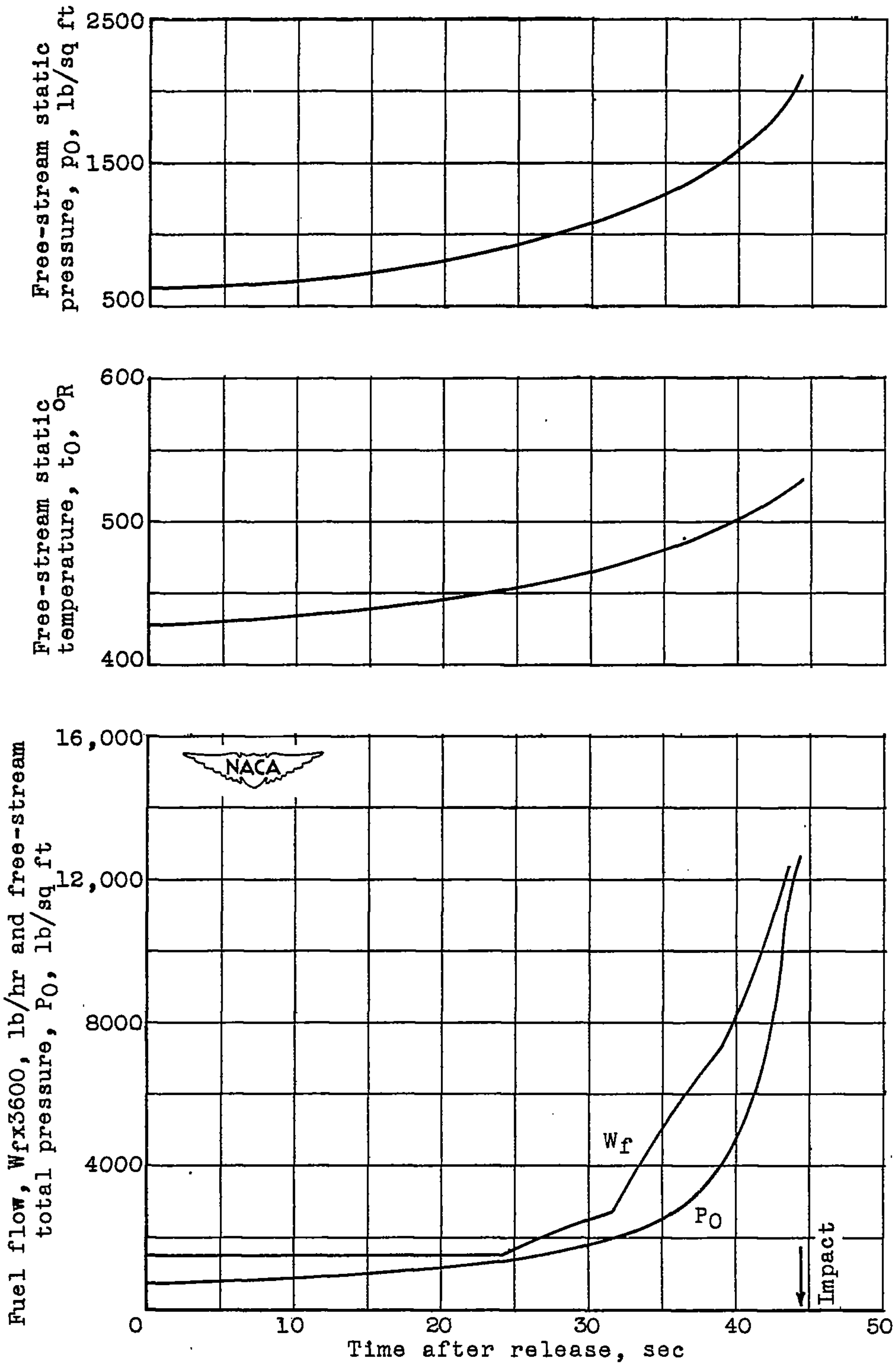

(b) Independent variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-C-5.

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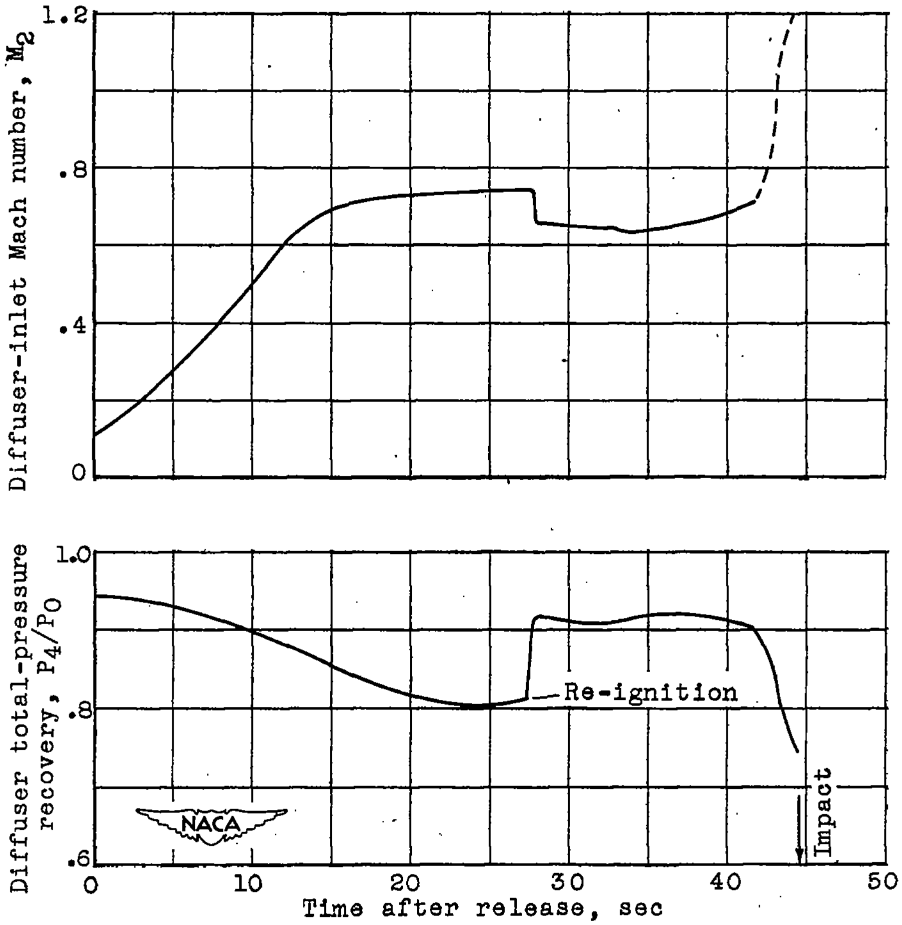

(c) Diffuser variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-C-5.

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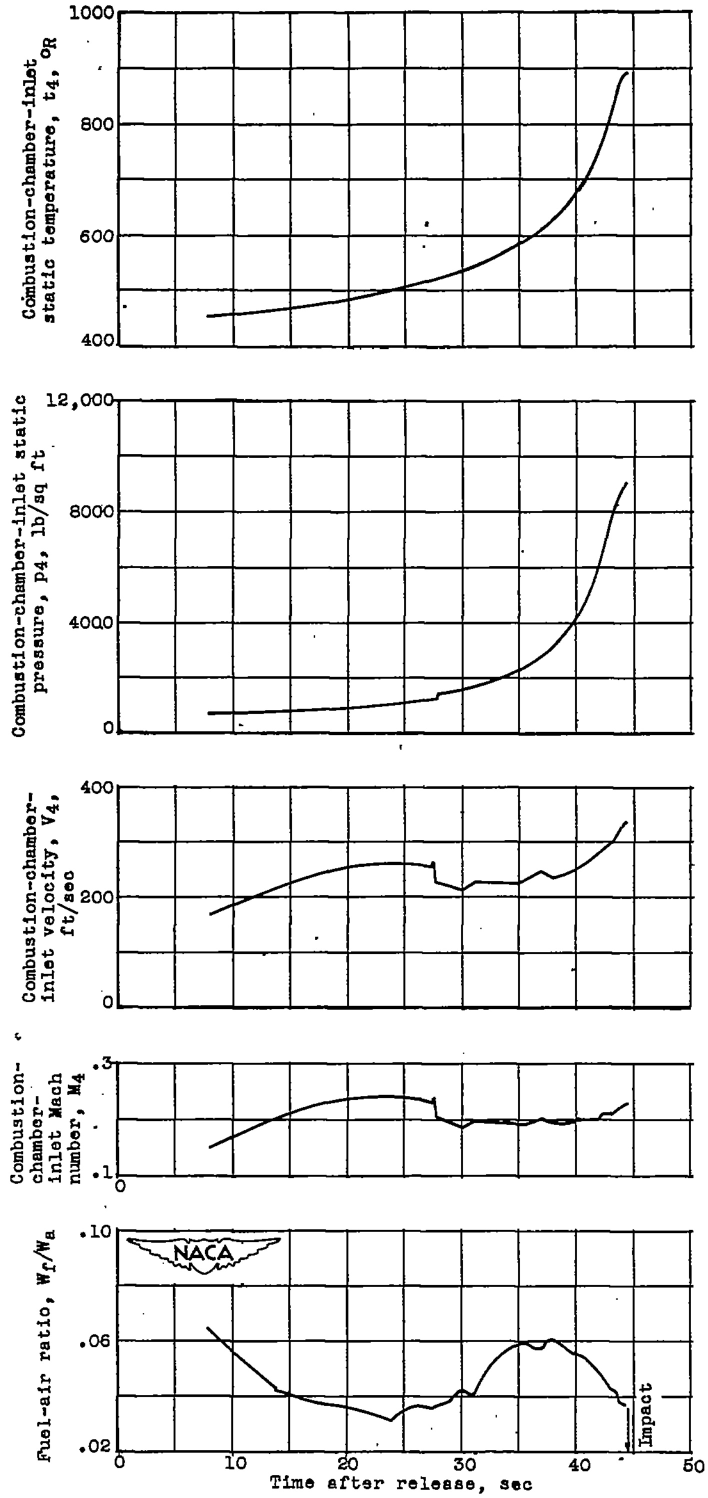

(d) Combustion-chamber-inlet variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-C-5.

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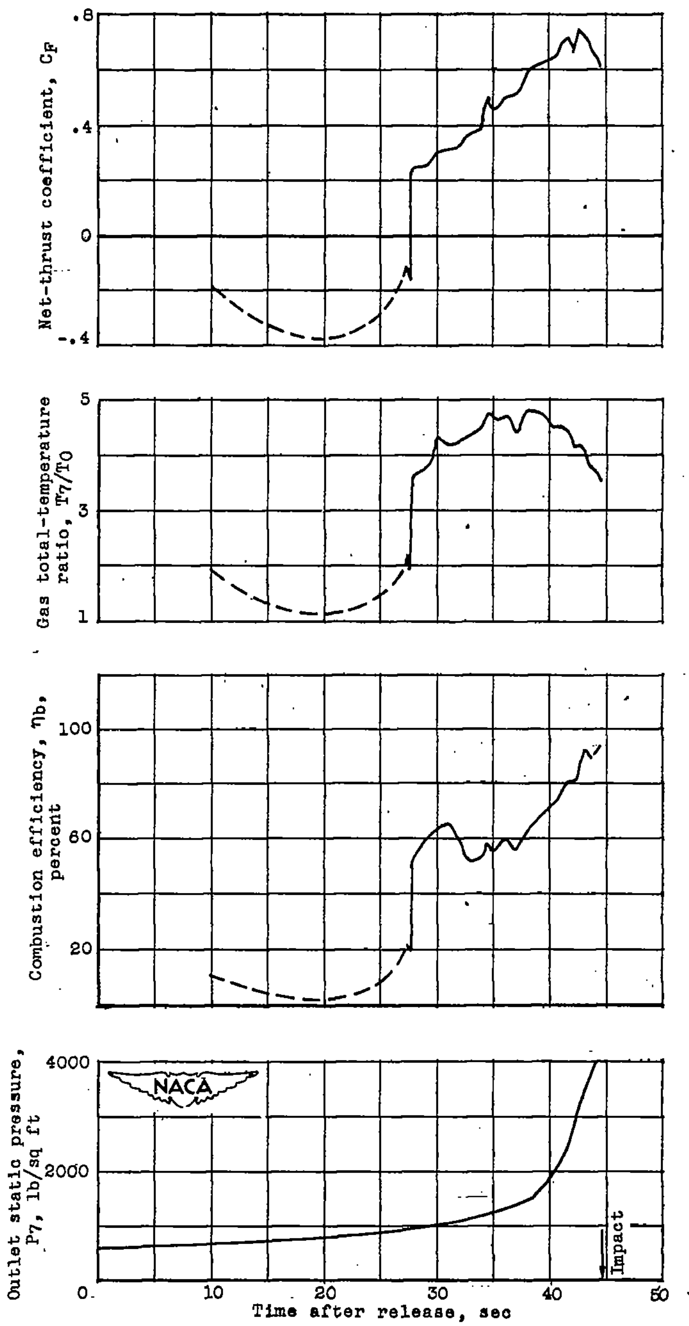

(e) Performance variables.

Figure 12. - Concluded. Time history of flight data and performance of ram-jet unit 16-C-5.

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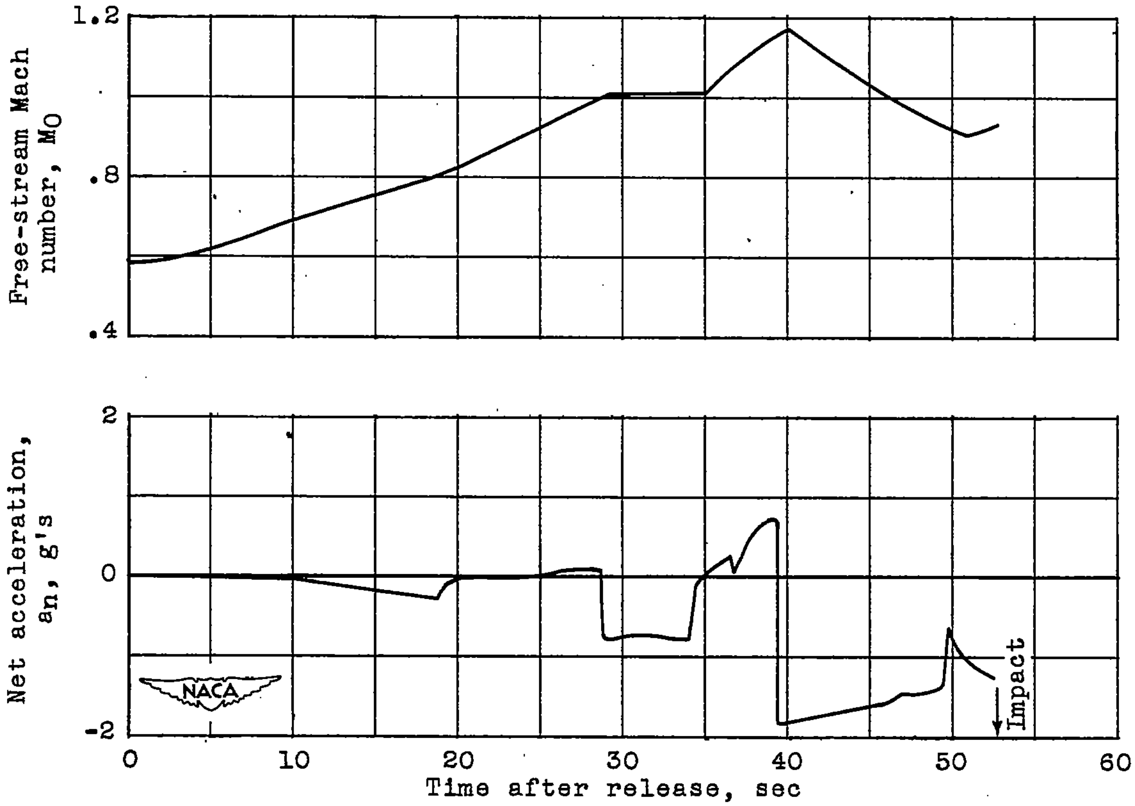

(a) Resultant flight conditions.

Figure 13. - Time history of flight data and performance of ram-jet unit 16-C-6.

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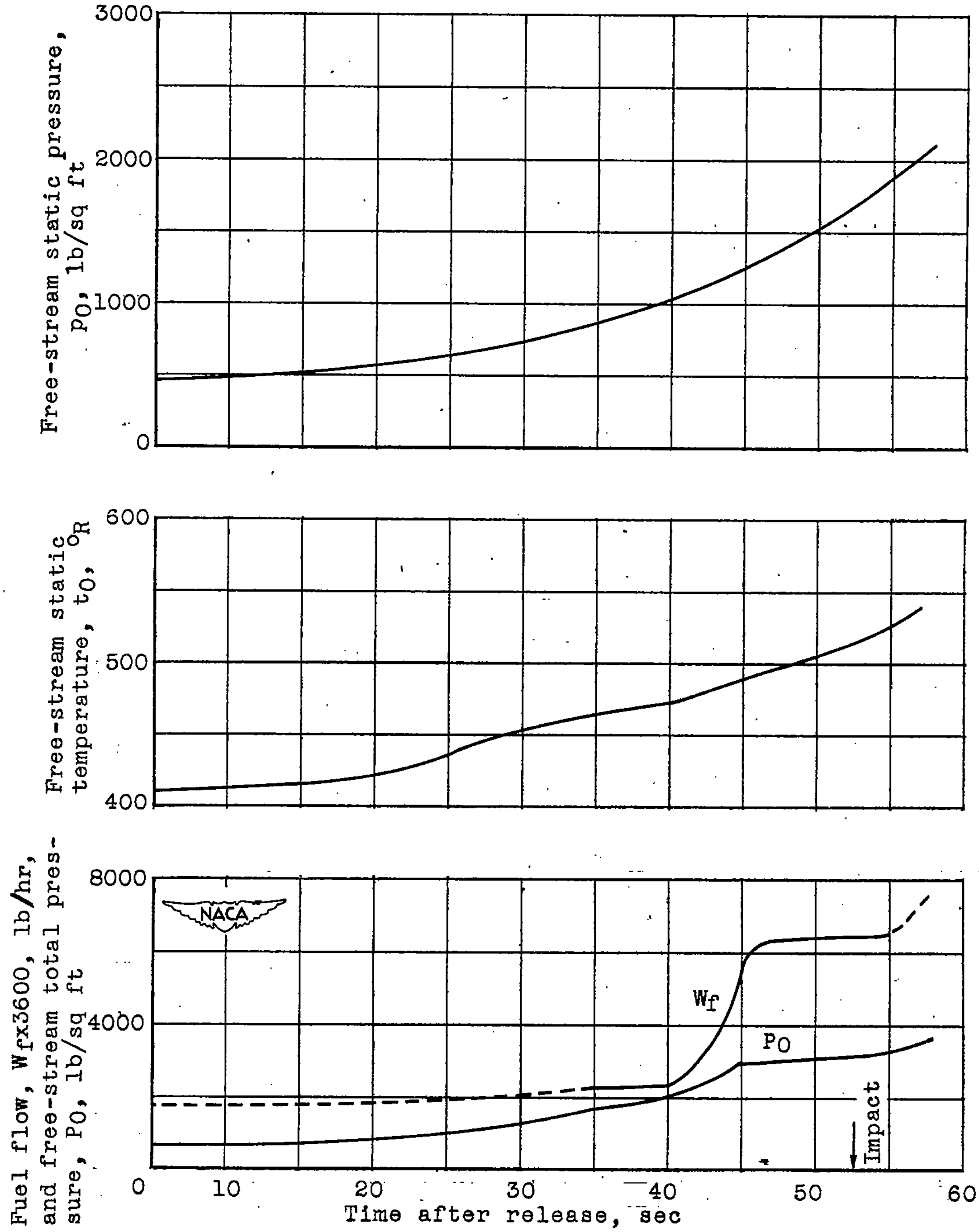

(b) Independent variables.

Figure 13. - Concluded. Time history of flight data and performance of ram-jet unit 16-C-6.

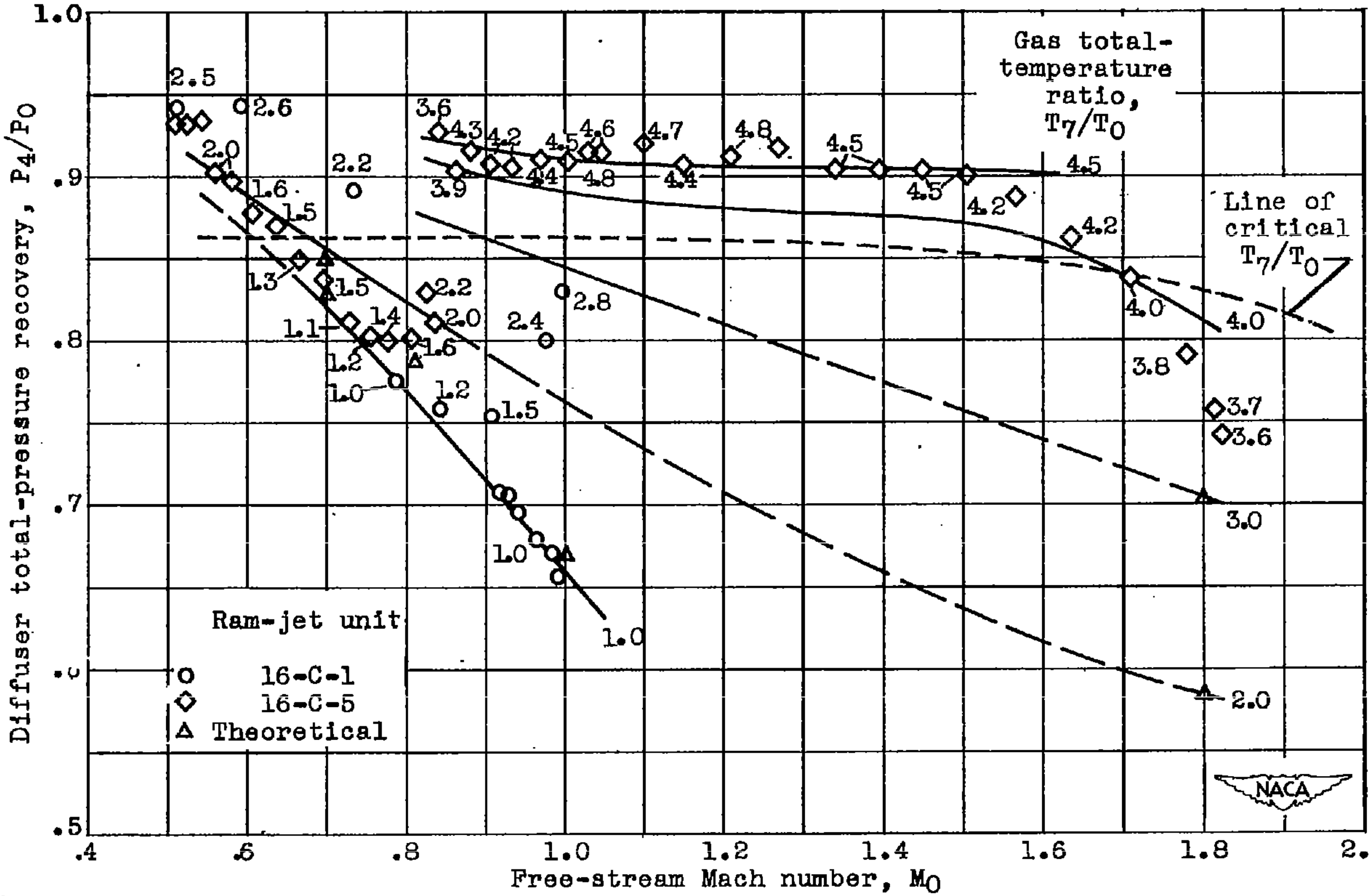

Figure 14. - Diffuser total-pressure recovery as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-C-1 and 16-C-5. (Values for data points are gas total-temperature ratios T_7/T_0.)

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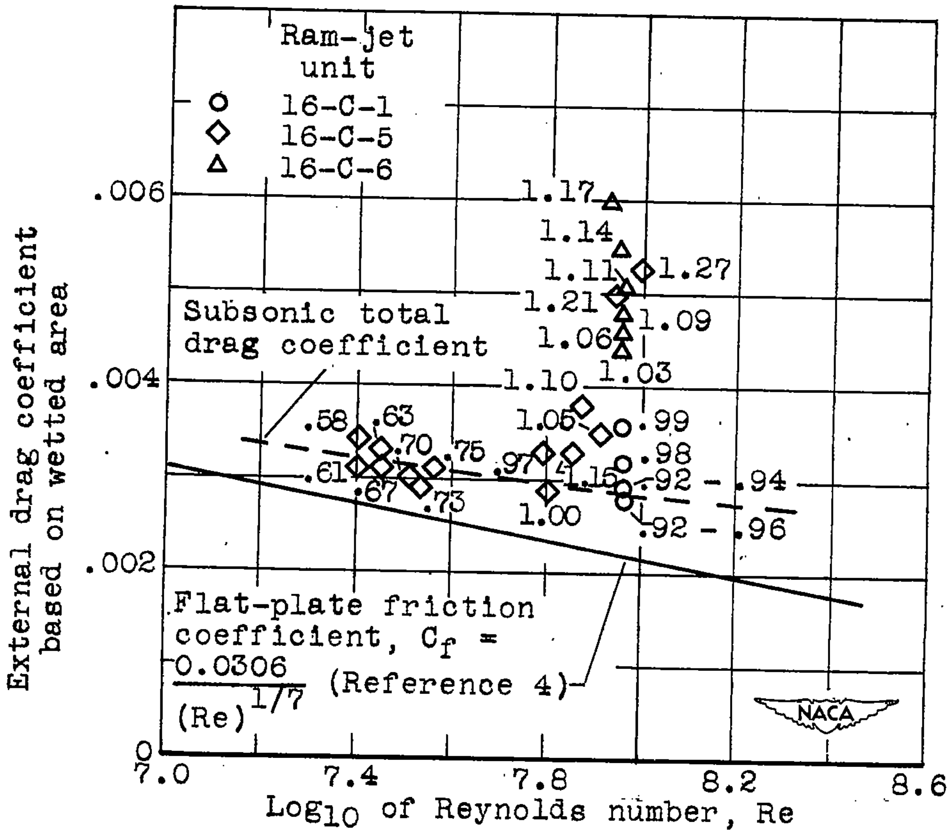

Figure 15. - Friction drag coefficient as function of Reynolds number and free-stream Mach number for ram-jet units 16-C-1, 16-C-5, and 16-C-6. (Values for data points are free-stream Mach number.)

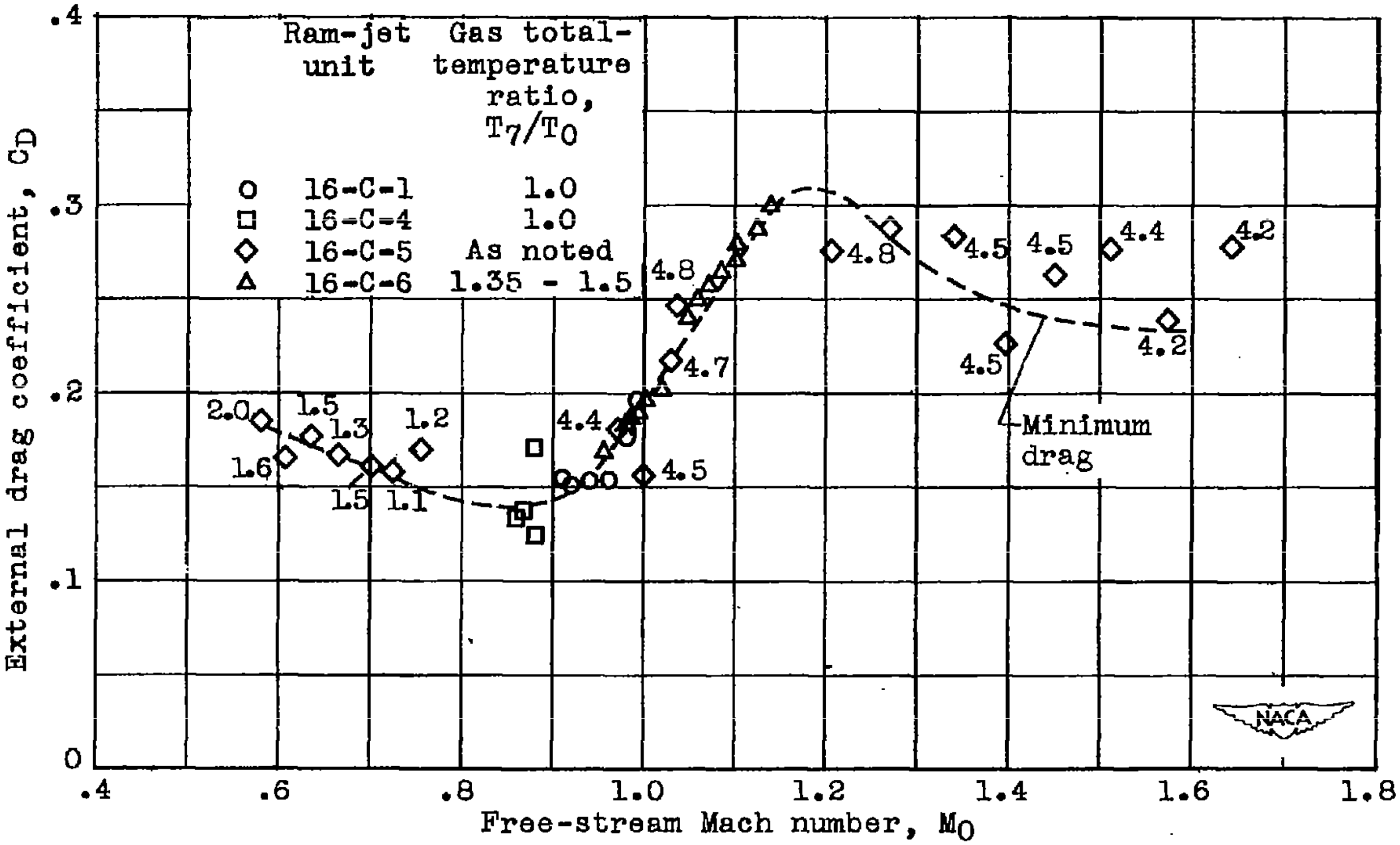

Figure 16. - External drag coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-C-1, 16-C-4, 16-C-5, and 16-C-6. (Values for data points are gas total-temperature ratios T_7/T_0.)

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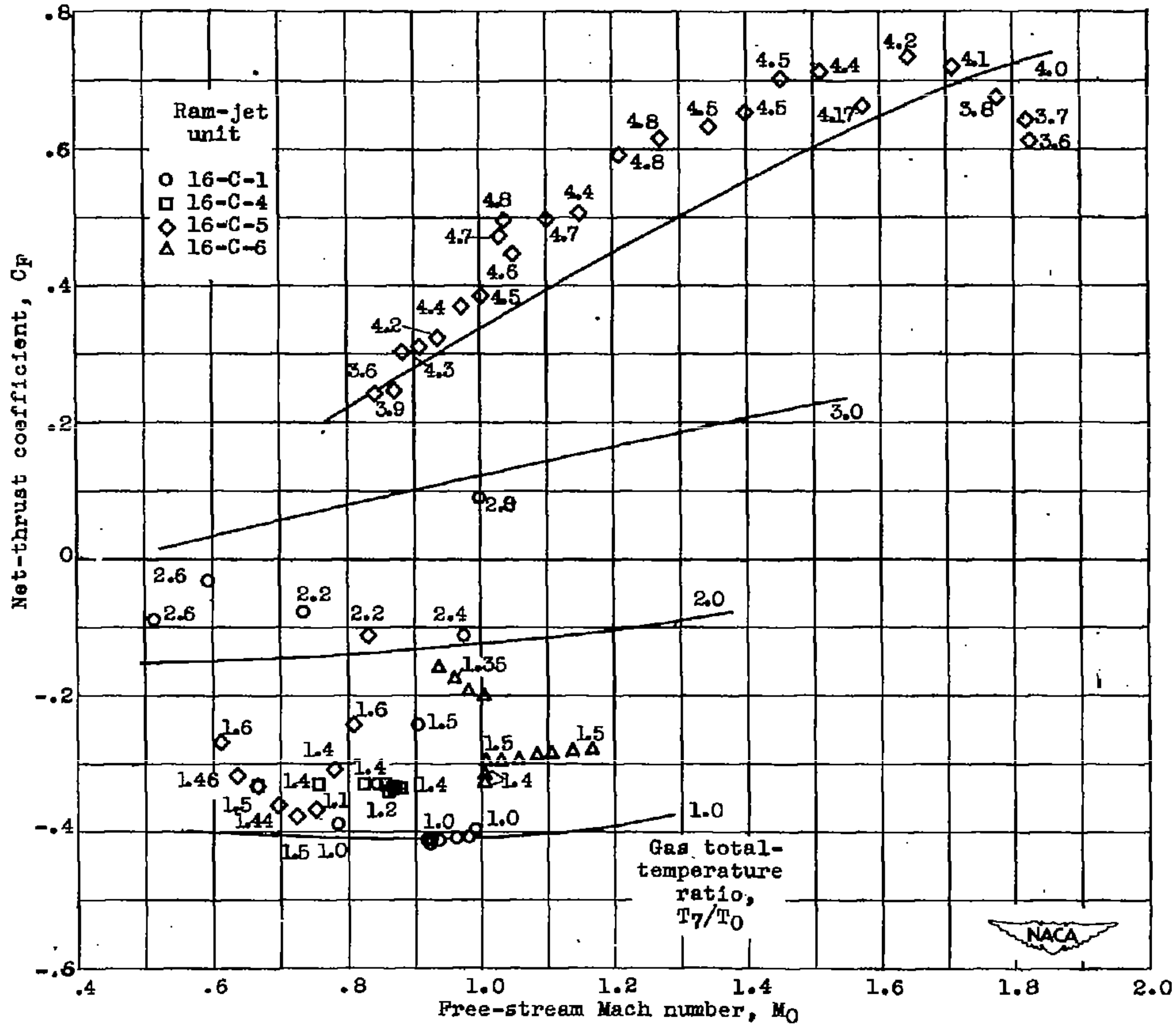

Figure 17. - Net-thrust coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-C-1, 16-C-4, 16-C-5, and 16-C-6. (Values for data points are gas total-temperature ratios T_7/T_0.)

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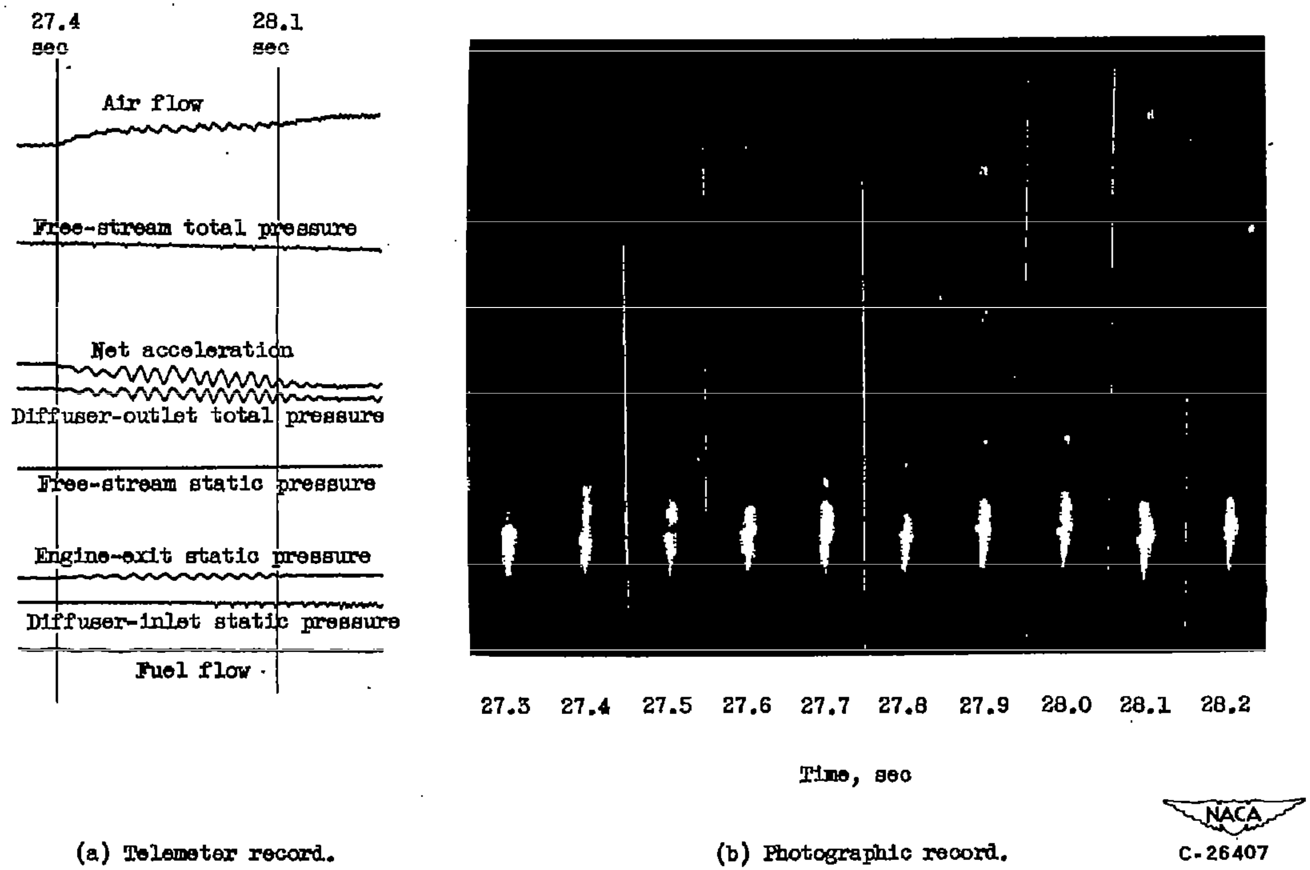

(a) Telemeter record.

(b) Photographic record.

Figure 18. - Ram-jet unit 16-C-5 with lean ignition: fuel-air ratio, 0.036; combustion-chamber-inlet velocity, 256 feet per second; combustion-chamber-inlet pressure, 1236 pounds per square foot; combustion-chamber-inlet temperature, 520° R.

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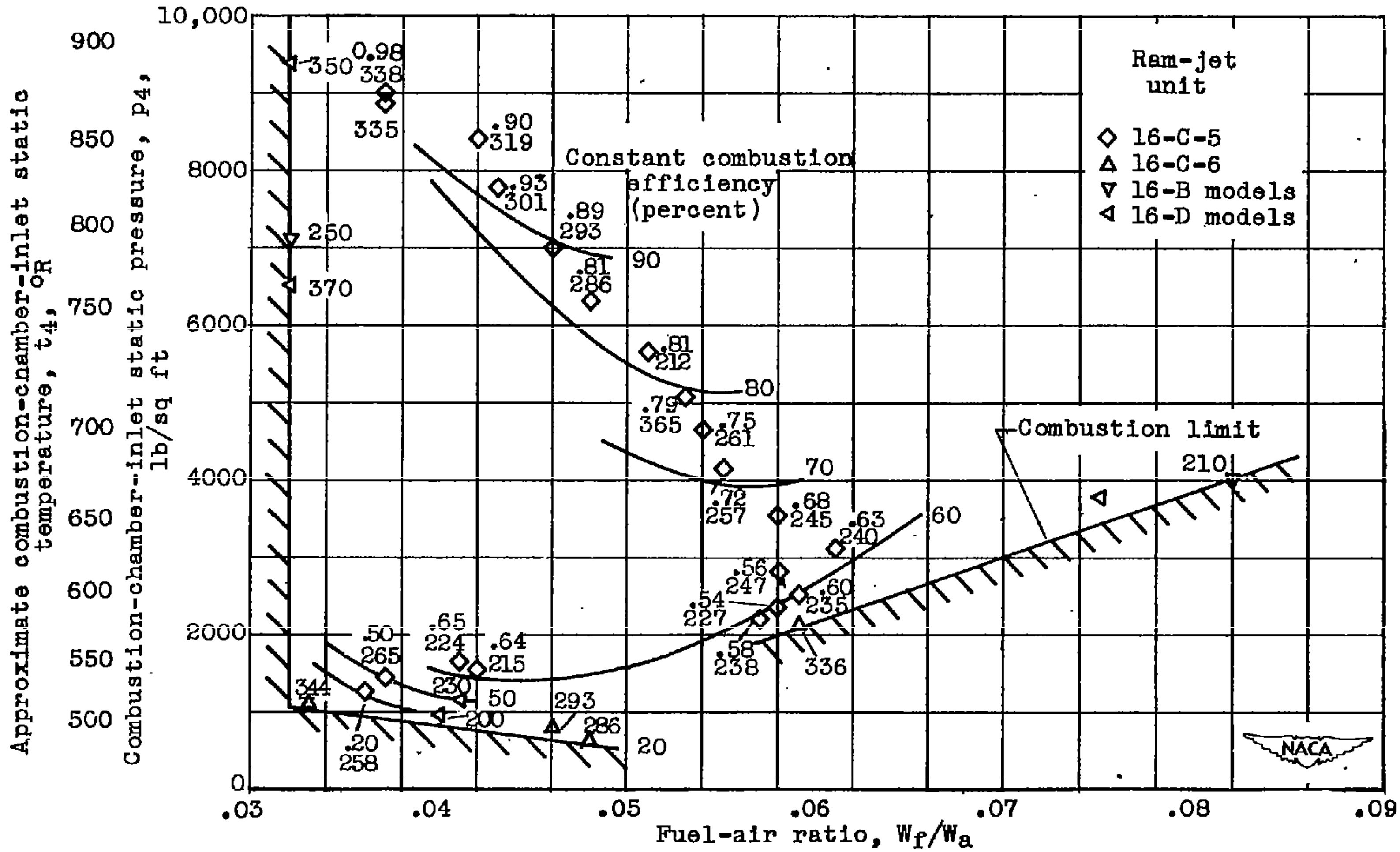

Figure 19. - Combustion performance. (Values for data points are combustion efficiency η_b, percent; combustion-chamber-inlet velocity V_4, ft/sec.)

[redacted]

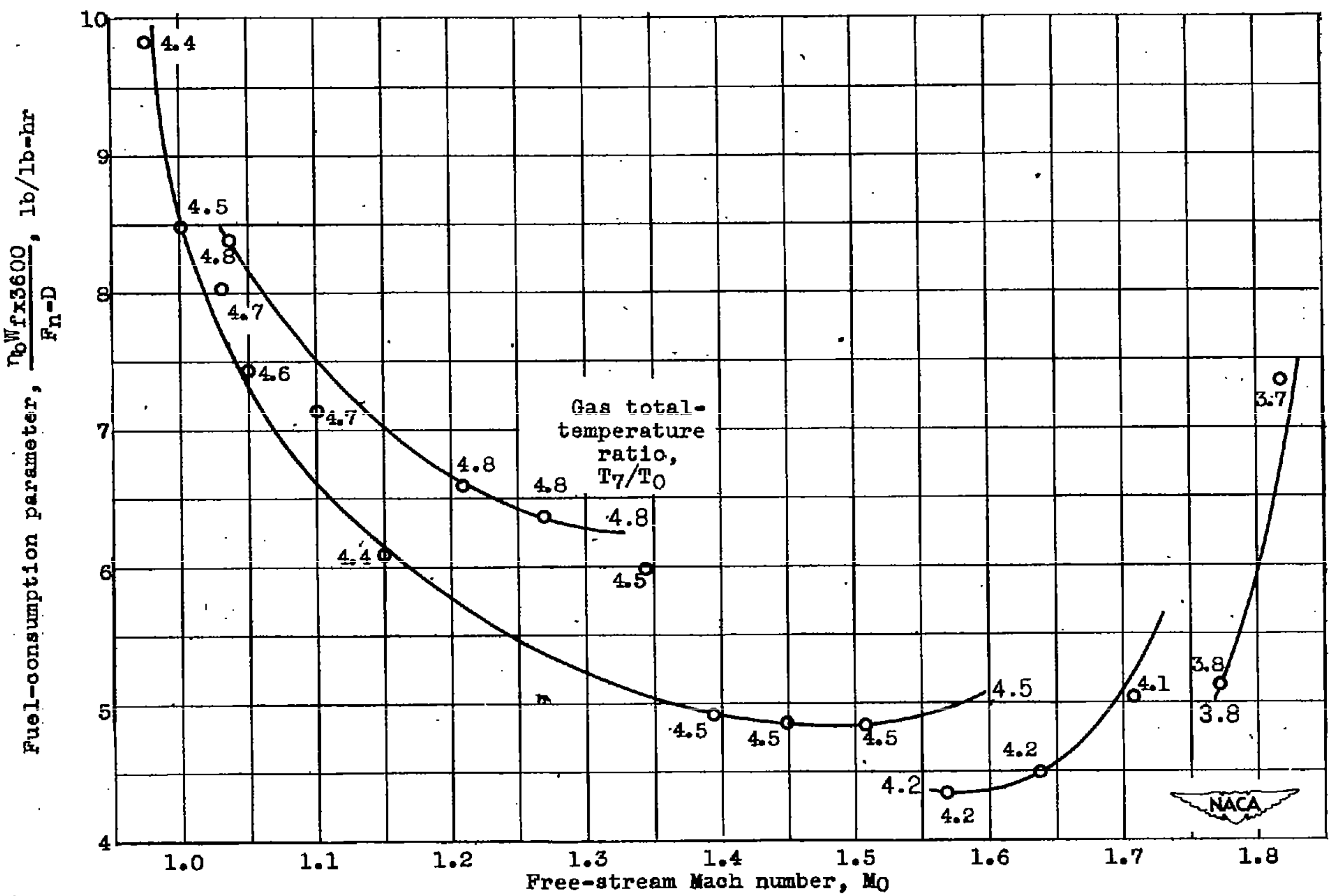

Figure 20. - Variation of fuel-consumption parameter with free-stream Mach number at various gas total-temperature ratios for ram-jet unit 16-C-5. (Values for data points are gas total-temperature ratios T_7/T_0.)